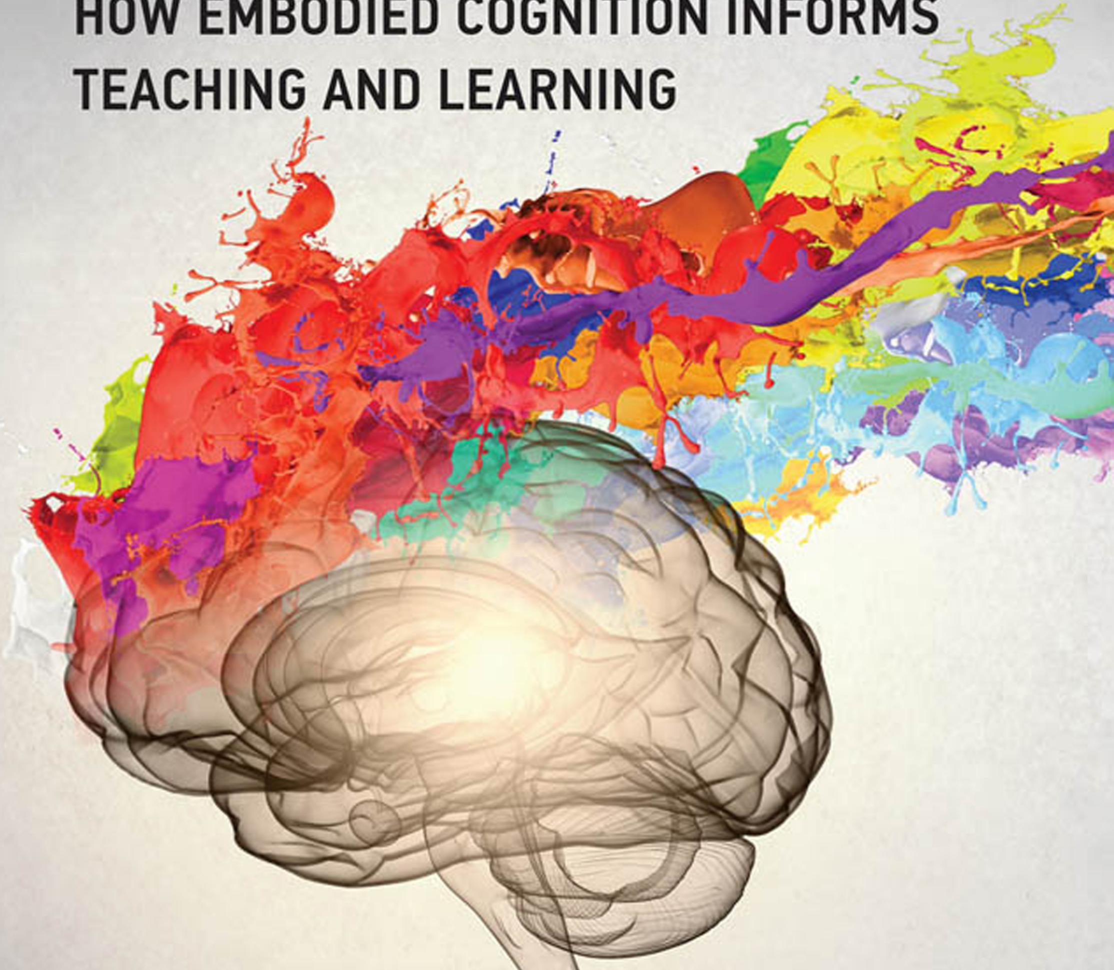
MOVEMENT MATTERS

HOW EMBODIED COGNITION INFORMS TEACHING AND LEARNING



EDITED BY

SHEILA L. MACRINE AND
JENNIFER M. B. FUGATE

Movement Matters

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How Embodied Cognition Informs Teaching and Learning

Edited by Sheila L. Macrine and Jennifer M. B. Fugate

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Sheila Macrine would like to dedicate this book to her husband, Nicholas, for his continued support. She is also dedicates this book to her son, Gavin, for his continued curiosity, sense of humor, and intellect. Jennifer Fugate would like to dedicate this book to her husband, Matthew, for his everlasting commitment and encouragement. She also dedicates this book to her young son, Connor, who has taught her the importance of movement—in play and in learning.

Contents

Acknowledgments xi
Foreword xiii
Lawrence Shapiro

Introduction 1
Sheila L. Macrine and Jennifer M. B. Fugate

I PHILOSOPHICAL AND THEORETICAL BACKGROUND

1 Embodied Cognition and Its Educational Significance 13
Sheila L. Macrine and Jennifer M. B. Fugate

2 Embodied Concepts: Basic Mechanisms and Their Implications for Learning and Memory 25
Markus Kiefer, Carmen Hofmann, and Petra A. Arndt

3 Embodied, Enactive Education: Conservative versus Radical Approaches 39
Daniel D. Hutto and Dor Abrahamson

II LANGUAGE

4 The Embodiment of Letter Perception: The Importance of Handwriting in Early Childhood 55
Karin H. James

5 Embodied Classroom Activities for Vocabulary Acquisition 77
Ligia E. Gómez and Arthur M. Glenberg

6 Educational Applications of Enacted, Embodied Approaches to Language Comprehension 91
Michael P. Kaschak and Amanda L. McGraw

7 **Reading, Writing, Technology, and Embodiment** 103
Anne Mangen and Antti Pirhonen

III STEM

8 **Seeing Is Achieving: The Importance of Fingers, Touch, and Visual Thinking to Mathematics Learners** 121
Jo Boaler

9 **Groups That Move Together, Prove Together: Collaborative Gestures and Gesture Attitudes among Teachers Performing Embodied Geometry** 131
Kelsey E. Schenck, Candace Walkington, and Mitchell J. Nathan

10 **Manipulatives and Mathematics Learning: The Roles of Perceptual and Interactive Features** 147
Andrea Marquardt Donovan and Martha W. Alibali

11 **Physics and Gesture: Spatial Thinking and Mutual Manifestness** 163
Colleen Megowan-Romanowicz

IV APPLIED TECHNOLOGY

12 **Responsive Teaching for Embodied Learning with Technology** 179
Virginia J. Flood, Anna Shvarts, and Dor Abrahamson

13 **The Need for SpEED: Reimagining Accessibility through Special Education Embodied Design** 197
Sofia Tancredi, Rachel S. Y. Chen, Christina Krause, and Yue-Ting Siu

14 **Immersive Learning Experiences in Augmented Reality (AR): Visualizing and Interacting with Magnetic Fields** 217
Rebecca Vieyra and Chrystian Vieyra

15 **Evaluating Embodied Immersive STEM VR Using the Quality of Education in Virtual Reality Rubric (QUIVRR)** 237
Mina C. Johnson-Glenberg

V SOCIAL COGNITION, EMOTION, MINDFULNESS

16 **Mirror Neurons and Social Implications for the Classroom** 261
Christiana Butera and Lisa Aziz-Zadeh

17 Beyond the Social Domain: Autism Spectrum Traits and the Embodiment of Manipulable Object Concepts 275
Charles P. Davis, Eiling Yee, and Inge-Marie Eigsti

18 Embodied Emotion, Emotional Granularity, and Mindfulness: Improved Learning in the Classroom 291
Jennifer M. B. Fugate and Christine D. Wilson-Mendenhall

Conclusion 307
Sheila L. Macrine and Jennifer M. B. Fugate

Resources 317
Contributors 323
Index 327

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Foreword

Lawrence Shapiro

In the movie *The Matrix* (1999), the characters Trinity and Neo find themselves on a rooftop looking for a way to rescue their companion, Morpheus. A B-212 helicopter sits idly by. “Can you fly that thing?” Neo asks Trinity. “Not yet,” she responds. Trinity then calls another companion and requests that he download into her brain a “pilot program.” Seconds later, she (or, at any rate, her virtual self) is flying the helicopter like a pro. But what information did that pilot program contain? Clearly Trinity *learned* something from the program. After all, before it was downloaded into her brain she could not fly a helicopter; afterward she could. But what, exactly, did she learn?

A natural way to interpret the scene is to conceive of Trinity’s brain as something like a computer. We know that a computer’s behavior can be modified with a program, which is simply a list of instructions that a computer is built to use in carefully designed ways. If you want your computer to do word processing, you feed it a word processing program, which contains instructions for copying, pasting, and formatting words. If you want your computer to crunch numbers, you download a spreadsheet program, which contains instructions for adding, multiplying, and averaging columns of numbers. In principle, then, there is nothing *too* far-fetched in the idea that Trinity could learn to fly a helicopter simply by having downloaded into her computational brain a program—a set of instructions—that describe all the various procedures involved in piloting a helicopter. If brains are computers, and if the various activities of which human beings are capable can be defined in terms of finite sets of instructions, then learning a new activity might be simply a matter of internalizing the right program.

Moreover, when we reflect on how we have in fact learned to do various things—bake a cake, multiply three-digit numbers, convert present-tense Spanish verbs into past tense—it does seem that we have been guided by explicit instructions. The instructions say to beat the eggs with the sugar, or to multiply the number in the singles column with each number above it, or to change the final *o* to an *e* in the first-person singular. Learning is nothing more than acquiring the right program. Teaching is nothing more than providing the program.

That these ideas seem pretty sensible, or at least familiar, might in part be due to the pervasiveness of the computer metaphor in modern society. For decades, it has been commonplace to speak of computers as "thinking," and of thinking as computing. Computers are artificial brains, and brains the "wetware" analogue of a computer's hardware. More significantly, the ideas that brains are computers and that cognition is a computational process have been central guiding principles in cognitive science since its inception in the latter half of the twentieth century. Traditional cognitive science has contributed immensely to our understanding of how minds work. However, despite its successes, traditional cognitive science has had a hard time accommodating a number of interesting findings—findings that have prompted researchers to seek a new paradigm for understanding the mind: embodied cognition. If we accept the conception of mind that emerges from the science of embodied cognition, then the download that spontaneously turned Trinity into a helicopter pilot consisted not of a list of instructions but of information of a very different sort. We will see that this shift in perspectives has implications for teaching and learning more generally.

A computational process, roughly, begins with an input of information, proceeds through instruction-guided operations on this information, and finishes with an output, which is the product of the operations on the input. Multiplication, for instance, is a paradigmatic computational process. An input might consist of the symbols 6 and 3. Operations on these symbols then result in an output of 18. The operations constitute an algorithm—a list of instructions that guarantee a particular result when applied to inputs of a given kind. The core commitment of traditional cognitive science is that the various cognitive capacities—perception, memory, language use, reasoning, and so on—can all be analyzed in terms of computational processes.

Just to consider a few examples, investigators of visual perception might wonder how three-dimensional vision arises (see, e.g., Marr, 1982). Objects in the world appear at relative depths: the book appears to be closer to me than the window but farther from me than the vase. But how is information about depth derived from the basically flat images on each of my two retinae? A computational explanation begins with the inputs—the points of light on each retina—and then hypothesizes an algorithm that operates on these points, perhaps by identifying matching points on each retina and measuring their disparity relative to each other. The output of the algorithm will be information about the relative depths of the objects that caused the images on the retinas.

Or perhaps a cognitive scientist wishes to understand how human beings recall whether a particular numeral is among those on a memorized list (e.g., Sternberg, 1969). The inputs to the recall process consist of a list of numerals that the person has memorized and then a "test" numeral. In recalling whether the test numeral is among those on the memorized list, a "comparison" algorithm will seek a match between the test numeral and the numerals on the list, outputting a "positive" result if a match is found and a "negative" result otherwise.

Just as the vision researcher might hypothesize different algorithms for recovering depth information from the inputs on the retinas, so too the memory researcher considers a variety of algorithms that might succeed in the recall task. Much of traditional cognitive science is focused on devising experiments that will reveal behavioral differences among the candidate algorithms that convert inputs into outputs. We might expect some algorithms for multiplication to require more time to execute than others or to breakdown in characteristic ways; so too the cognitive scientist expects details of a subject's behavior (reaction times, patterns of performance errors) to shed light on which of several candidate algorithms underlie that individual's psychological capacities. Explaining a cognitive capacity, for a traditional cognitive scientist, involves detailing the steps in the algorithm that converts the inputs to the capacity into the appropriate outputs. Justification for the explanation consists in the often-ingenious experiments that reveal why it must be *this* algorithm that is functioning rather than some other.

I hope these examples have provided enough of the "flavor" of traditional cognitive science to reveal some of its more implicit commitments. The first commitment concerns the role of the cognizer's environment. There is a sense in which the environment does not have much or any significance for cognition. The inputs to a cognitive process "begin" at the cognizer's sensory surfaces. Information about the relative depths of objects in the world, for instance, is derived from points of light on the retinas. Imagine that the same points of light were projected onto a subject's retinas not from their reflection from surfaces in the world but through some artificial means. As far as the computational algorithms that operate on these inputs are concerned, there is no reason to distinguish between the "genuine" inputs and the artificially induced inputs. The algorithm is "cut off" from the world and goes through the same steps regardless of the source of the inputs over which it operates. Indeed, cognitive scientists often capitalize on this fact when designing experiments to analyze perceptual capacities. A typical experiment has a subject sitting in front of a computer monitor or with goggles covering her eyes so that the inputs to the visual algorithms can be carefully controlled. The guiding assumption is that a subject's interaction with a "real" environment is not important for understanding perception.

Also, of little significance in traditional cognitive science are properties of the subject's body. Just as all inputs to a computer—whether arriving through a keyboard, a camera, a touch pad, or a microphone—ultimately get translated into a common code over which the computer's programming runs, so too, the traditional cognitive scientist assumes, the code over which cognitive algorithms run carries no trace of the body that produces them. Additionally, the nature of the cognizer's body—the number of limbs it possesses, its posture, its orientation—have at best an incidental effect on cognitive processing, an effect that is filtered through whatever impact these properties have on the brain. In themselves, they do not qualify as proper constituents of the cognitive process.

Embodied cognition marks a radical shift in how to conceptualize cognitive processing, and, correspondingly, how to understand the significance of the environment and the body in this processing. Turning first to the increased emphasis that embodied cognition places on the environment's role in cognition, we might begin with recognition of J. J. Gibson's work in ecological psychology (e.g., 1966). In his theory of perception, Gibson rejected the very idea that makes traditional cognitive science seem so compelling—that the inputs to sensory systems require computational processing in the first place. In Gibson's view, enough information is present in the environment and is packaged in such a way that organisms do not need to modify it with computational processes to make use of it. The perception of depth, for instance, does not require an algorithm that matches points on two retinas and measures their disparity. Depth will be detected "automatically" from the information contained in light reflected from texture gradients in surfaces that extend from the perceiver and from the patterns of changing stimulation on the retinas as the perceiver moves through the environment.

Influenced by Gibson's resistance to computational explanations of cognition, proponents of embodied cognition often attribute cognitive abilities to a tight and constant connection between a subject and features of the subject's environment. By virtue of such a connection, the idea that perception requires computational transformations of sketchy sensory representations of the world loses its appeal. Taking center stage now are investigations of interactions between a subject and the environment that suffice to create patterns of changing stimulation of a sort that directly specifies features of the world. For instance, the ability of an outfielder to position herself at the precise location where the fly ball will drop from the sky is not explained in terms of computations her brain performs involving the location of the batter, the trajectory of the ball, the velocity of the ball, and so on. Rather, the outfielder moves to the correct location simply by constantly tracking a single variable: the upward acceleration of the ball. When the upward acceleration of the ball appears constant, the outfielder will be standing where she can intercept the ball (Shaffer & McBeath, 2005). Similarly, roboticists have achieved remarkable success having replaced traditional "computation-heavy" architectures with designs that combine the activities of simple modules, each of which might track a single feature of the environment, such as the distance from a wall or whether an obstacle is straight ahead (Brooks, 1991). The implementation of navigational abilities in robots, once thought to require internalized maps from which routes could be calculated, now adopts the anticomputationalism that Gibson promoted.

But in addition to its focus on the kinds of subject-environment interactions that can replace computational processes, many embodied cognition researchers conceive of the environment as itself a component in cognitive processing (Clark & Chalmers, 1998). While traditional cognitive science locates thought processes entirely within the computational brain—thus lending plausibility to the idea that Trinity might learn to fly a helicopter by means of a program that is downloaded into her brain—embodied cognition encourages us to take seriously the idea that a cognitive system can spread beyond the brain, incorporating parts of the world as well as the subject's body. Multiplying large numbers, for instance, is a task that very few human beings can do in their head. The use of paper and pencil, or a calculator, is ordinarily an ineliminable step in the process. Building on this observation, embodied cognition researchers have begun to view the cognitive processes that occur in the brain as only one element in a larger system, the totality of which, including aspects of the world and body, constitutes the proper unit of explanatory interest. From this perspective, brains have been designed over evolutionary time to work with and exploit properties outside of themselves for the purpose of "pulling together" a cognitive system in which they are just one (important) part. Investigations of cognition, accordingly, must shed their brain centrism in favor of analyses that seek to understand how cognition emerges from a brain that actively collaborates with non-neural resources.

Still another reorientation that embodied cognition urges concerns the nature of the neural processing that—to whatever extent—contributes to cognition. Traditional cognitive science preserves the idea that the neural "symbols" over which the brain's computational processes operate are "amodal." This returns us to the earlier point that the originating source of inputs to a computer—keyboard, camera, microphone, or whatever—makes no difference to the form in which these inputs are ultimately encoded. In the end, it is all "1s and 0s." Lost in this process of transduction is the fact that some of this input was initially visual in nature, some auditory, some tactile. Put another way, if all you could see was the code, you would have no idea whether it reflected visual, auditory, or tactile properties because information about these “modes” is not retained in the code itself. In keeping with this idea is an analysis of *concepts,* which are often construed as the building blocks of thought, as having no special connection to the bodies of their possessors. The concept *apple,* for instance, is encoded in the same *kind* of way as the concept *chicken* or as the concept *kick.*

By contrast, the embodied view of concepts draws on neurological and behavioral evidence that suggests a “modal” form of encoding (Barsalou, 1999). The thought *apple* is constructed from activity in the sensory and motor areas of the brain that had become activated when a person originally interacted with an apple: areas of visual cortex that respond the apple’s color and shape, areas of auditory cortex that respond to the sound of biting into an apple, areas of premotor cortex that control how one grasps an apple, and so on. Similarly, the thought *kick* activates areas of premotor cortex that would be engaged when involved in a kicking action (but, of course, this activity is suppressed so that the thought does not actually cause your leg to move). Cognition is thus tightly integrated with and indebted to the particularities of a thinker’s body. Agents whose bodies or sensory capacities differ from those of typical human beings would, by hypothesis, think differently about the world. The concept *apple* for an agent with fins rather than hands, or who lacked color vision, would not be constructed with the same packets of modal information about graspability, color, and so on that constitute the human concept *apple.*

With some sense now of how embodied cognition seeks to recharacterize the nature of cognition and, correspondingly, the proper means for its investigation, we can revisit Trinity on that rooftop and ask again about the contents of the program that has been downloaded into her brain. What information did the program contain by virtue of which Trinity is suddenly able to fly a B-212 helicopter? The embodied cognition theorist would, of course, reject the idea that the program is something like a detailed description of all the steps involved in piloting a helicopter—much like a recipe might describe the steps involved in baking a cake. If, as we are to imagine, Trinity acquires the ability to fly the helicopter, it will be because the program has loaded into the sensory and motor regions of her brain the sights, sounds, and motions that a seasoned helicopter pilot with a body roughly like hers will have experienced when flying. Moreover, the program will have been tailored to produce the kinds of actions that can exploit the resources on the helicopter—the dials, gauges, pitch sticks, and pedals—turning them literally into parts of the cognitive system from which the capacity to fly the helicopter emerges. Additionally, it will have equipped her to identify and attend to those variables in her environment that specify the precise actions that successful flight requires.

Insofar as this embodied view of how Trinity might have learned to fly a helicopter is correct, it contains lessons for educational practices more generally. Most obviously, if cognition develops through agent-environment interactions, then "old school" instruction, in which students sit at their desks observing teachers at blackboards or memorizing formulas or studying graphs, should be replaced with a method of instruction that recognizes and capitalizes on the contributions that bodies and environments make to cognition. Happily, such efforts are already underway. Psychologists and educators who have embraced embodied views of cognition now seek to understand how a student's gestures might indicate something about their grasp of mathematical concepts, and how a teacher's gestures might in turn illuminate these concepts (Goldin-Meadow & Singer 2003; Walkington et al., 2014; see Shapiro & Stolz, 2019, for discussion). Psychologists have designed experiments to test which motions—writing letters by hand or typing them on a keyboard—are most likely to improve future reading skills (Keifer et al., 2015; see Fugate et al., 2018 for discussion). They have asked young readers to manipulate toys in order to simulate parts of a story, revealing a boost in comprehension as a result (Glenberg et al., 2011).

Whatever the fate of embodied cognition—whether it ends up the "true" theory of cognition—there is no doubting that it has inspired new and promising educational strategies that have already proven superior to the "learning by recipe" route that seems a natural complement to the computational picture of cognition. The chapters of this book provide convincing evidence that this is so.

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Introduction

Sheila L. Macrine and Jennifer M. B. Fugate

Movement makes reason lucid
—Hozier, 2019

Understanding the mind and how thinking occurs has been a challenge for philosophers, scientists, theorists, educators, and artists throughout history. Ideas about how we learn have been mainly theoretical and intuitive. With the current advances in neuroscience, however, many unanswered questions are being addressed. As a result, a paradigm shift is taking hold in human cognition, pointing to a new science-based understanding about the way we think and, ultimately, the way we learn. That shift includes a move away from traditional notions of the mind to an "embodied" model of human thinking and learning. Backed by scientific evidence from neuroimaging techniques, there is a growing movement to not only understand thinking as inseparably linked with the body and the environment, but also to reimagine the learning that follows. When thinking (i.e., cognition) is embodied, it is deeply dependent on features of the physical body of the learner. Said another way, a learner's body plays a significant causal or physically constitutive role in cognitive processing (Wilson & Foglia, 2016). Therefore, the body (and the brain's representation of that information) is key to understanding how thinking occurs (Kumar, 2018).

The French philosopher Merleau-Ponty (1962) posited that an embodied approach emphasizes an intercorporeality of the "subjective, lived-body" and that cognition cannot be understood without the body's engagement with the world—a type of "enfleshment" of thought (see Gallagher & Varela, 2003; Leitan & Murray, 2014; Macrine, 2002; Marshall, 2008). For Merleau-Ponty, thinking is manifested, learned, and even relearned through bodily experiences (Bahler, 2016; Leitan & Chaffey, 2014). It is this philosophical theory of embodiment that eventually evolved into a testable theory in cognitive science called "embodied cognition" (Fincher-Kiefer, 2019). Embodied cognition scholars argue that the body is indeed essential in the production of cognition (Varela et al., 1991) and that cognitive processes are based on—or are at least moderated by—sensorimotor processes (Barsalou, 2016; Mahon & Caramazza, 2008; Zona et al., 2018). Put differently, our physical interaction with the world influences or—in some cases—even determines our cognition (Kemmerer et al., 2013; Shapiro, 2014). Indeed, previous researchers have theoretically recognized that cognition is not only embodied but also socially constructed (Piaget, 1977; Vygotsky, 1978), situated (Lave, 1988), and culturally dependent (O'Loughlin, 1995; Rogoff, 1990). In addition, others pointed to the need for embodied metaphors (Lakoff & Johnson, 1980), concrete and hands-on experiences (Dewey, 1938; Montessori, 1912, 1973), such that the body is seen as the center of knowledge (James, 1890, p. 154). Further, Gibson (1979) argued that the person and the environment are mutually dependent on one another. Today, with advances in neuroscience, we have evidence confirming embodied views of cognition based on bodily and neural processes of perception, action, and emotion (Anderson, 2018; Aziz & Gomez-Djokic, 2016; Glenberg et al., 2013; Hauk et. al., 2004; James, 2010; Niedenthal, 2007; Niedenthal et al., 2010).

Although there are many "flavors" of embodied cognition, most recognize that thinking is grounded within the body and the environment, and that knowledge is simulated either directly or mediated by mental representations (for some examples, see Abrahamson & Lindgren, 2014; Barsalou, 1999, 2008; Clark, 2008; Gallagher as cited in Rowlands, 2010; Glenberg et al., 2005; Menary, 2010; Shapiro, 2011, 2014, 2019; Wilson, 2002). Recently, embodied cognition has expanded to incorporate the collective term "4E cognition," in which cognition is understood as not only "*e*mbodied," but "*e*mbedded" within a context, "*e*xtended" beyond the individual through enculturated practices, and "*e*nacted" as part of a dynamic system in which the body is self-producing and adaptive (see Hutto & Abrahamson, chapter 3 in this volume; Gallagher in Rowlands, 2010; Glenberg et al., 2005; Shapiro, 2014). So what does this mean for learning, and what are the implications for education?

Our current educational delivery systems (i.e., teacher education, teaching pedagogy, curriculum, environmental design, and educational psychology) and approaches can be traced back to "disembodied" views of human thinking. Accordingly, perceptual, sensory, and motor systems were presumed to be irrelevant in understanding brain processes (Wilson, 2002; Woodward et al., 2009). As a result, thinking was considered to be "limited" by the bodily senses and had to be freed from the corporeal trappings of the physical world (Young & Whitty, 2010).

For example, behaviorist theory prioritized stimulus-response action, which basically removed the individual from the equation and focused solely on action and prescribed responses. This led to passive transmission models of learning in the 1940s and early 1950s. Even with the onset of the cognitive revolution, passive learning continued to dominate, although the ideas of stimulus-response were now thought to be mediated by the brain. By the mid-1950s, information-processing models of cognition began to take root, and cognitive processes were likened to software computations (see Turing, 1950; Miller, 2003). As a result, thinking was now viewed as a *computation* process, with perception seen as the *input* and action as the *output.*

These early computer metaphors of cognition have evolved into the present day's computational models, yet few consider the person as central to the process. The goal of this kind of computational modeling is to infer the structural and functional properties of a cognitive process from the behavioral data thought to be generated by that process (Pitt et al., 2002). Yet these working models still mostly view thinking as amodal (symbolic) computations that lack connections to the individual's body and sensory systems (Fodor, 1975, 1998), and they often fail to correspond to the semantic properties of mental states specific to human understanding.

While theories of embodied cognition continue to emerge, the American classroom has not kept pace. Teaching pedagogy and curriculum continue to view learning as abstracted and separate from the body. As a result, classroom teaching continues to rely on presenting and learning disembodied concepts, without the engagement of the sensory motor systems or understanding how the body influences internalization of these concepts (see Macrine & Fugate, 2020, for a recent review).

Alternatively, an "embodied learning" paradigm suggests that actions, emotions, sensations, and environment can influence what is learned. In addition to active bodily based learning, embodied learning can also be achieved through simulations, which are aided by the brain's mirror neuron system (see Butera & Aziz-Zadeh, chapter 16 in this volume). As an example, observing the actions of a teacher results in the neural underpinnings of action observations and simulations (see Barsalou, 1999).

This Volume

The goal of this book, *Movement Matters,* is to explain/translate the latest empirical and clinical research on embodied cognition and to demonstrate how embodied teaching and learning principles naturally follow. That said, *Movement Matters* presents a space where neuroscience, psychology, cognitive science, and technology meet education to inform learning theory and to inspire an embodied approach to teaching the whole person. To accomplish this, we adopted and adapted an emerging approach called translational science research, historically found within the biomedical disciplines (McGaghie et al., 2012), to elucidate empirical and clinical findings for the public (NIH, 2020).

Such translational approaches have already been proven successful in the development of effective tools and interventions in the biomedical fields (NCATS, 2017). In other words, translational science (*bench to bedside*) is instrumental in closing the bio-medical research gap and is devoted to interpreting basic research findings to be used for tools, interventions, diagnoses, treatments, and prevention (Munro & Savel, 2016).

In 2013, Henry Roediger presciently wrote, “In an ideal world, Cognitive and Educational Psychologists would have created a translational educational science that would be eagerly adopted by education, schools and educators who would want to improve education on the basis of the latest research findings” (p. 1). He added that although such translational science has helped to disseminate new biomedical discoveries to broad audiences quickly, this has not been the situation in education despite more than a century of relevant psychological research (p. 1).

Evidenced-Based Practice

The call for research and evidence-based practice in education can be found in the No Child Left Behind Act of 2002, which mandated that “scientifically based” research be the norm for classroom instruction. Its updated replacement, the Every Student Succeeds Act of 2015, called for “evidence-based” interventions that are proven to be effective in leading to desired outcomes—namely, improving student achievement. Further, one of the nation’s foremost education researchers and policy analysts, Linda Darling-Hammond has stated that the rapid pace of our knowledge of human development and learning has impacted the emerging consensus about the science of learning and development and increased our opportunities to shape more effective educational practices (Darling-Hammond et al., 2020). Yet, she added, to take advantage of these advances requires integrating insights across multiple fields and connecting them to our knowledge of successful approaches.

To face these challenges, we adapted a model of translational science (Rubio et al., 2010) called *Translational Learning Sciences Research* (Macrine & Fugate, 2021) specifically to address evidenced-based research on embodied cognition in an applied format for educators. We argue that this collection is the first to systematically gather, collate, translate, and disseminate the latest embodied research geared toward improved learning outcomes. It also shares some of the most significant breakthroughs and applications that recent embodied cognition research has made on the science of learning across content areas.

In this volume, we apply our model to educational, psychological, and neuroscience research to inform embodied teaching and learning pedagogy for the classroom. It has four major goals: (1) to translate and inform the reader on the latest research in embodied cognition; (2) to develop and create appropriate embodied curriculum and instruction to improve teaching and learning outcomes; (3) to create resources and tools to develop a better understanding of embodied teaching and learning; and (4) to eventually develop taxonomies to track implementation and outcomes, which will assess whether competencies are being met (adapted from Rubio et al., 2010).

To accomplish this, our contributors specifically review and report on the impact of sensorimotor activity in the academic content areas of language, STEM (science, technology, engineering, and mathematics), applied technologies, and social and emotional competencies. Each of the contributors presents their embodied cognition research within these areas and translate their findings for classroom application. In doing so, we hope to encourage educators, educational psychologists, and others involved in schooling to adopt, apply, and develop their own embodied educational pathways. As a result, this book demonstrates how learning can be brought to new heights when the principles of embodied cognition are empirically applied to learning theory and teaching pedagogy. Finally, this collection helps us to understand what we know about how we learn and how this knowledge should inform the way we teach.

That said, embodied cognition represents one of the most important research programs in contemporary neuroscience and cognitive science. *Movement Matters* responds by translating the latest research on embodied cognition and critically examines its implications for classroom learning and teaching pedagogy. This book, written by a distinguished group of international scholars and emerging researchers, both charts embodied cognition's conceptual and philosophical roots and interprets and translates the supporting empirical evidence into effective teaching and learning strategies. The aim of this volume is to begin to build interdisciplinary connections among the theoretical and applied advances in the field of embodied cognition with applications for education and the Learning Sciences. Mindful of the fact that this research cuts across multiple disciplines and is rapidly expanding, *Movement Matters* is both a timely and important collection for educators and scholars. It bridges the gap between research and curriculum-content silos of knowledge by bringing together experts from all content areas in one collection. The goal of this book, therefore, is to help educators better understand the current scholarship and research in the new Learning Sciences—specifically, embodied cognition and its extensions, the "4E's" of cognition (Gallagher as cited in Rowlands, 2010).

Organization

These are indeed exciting times for education, where our previous understanding of the importance of the body in learning was mostly theoretical (i.e., Montessori, 1973; Piaget, 1977; Rogoff, 1990; Vygotsky, 1978). Now behavioral and neural evidence from psychology, neuroscience, cognitive science, and artificial intelligence has empirically supported these assumptions. Consequently, all these fields have undergone paradigm shifts in their view of the way knowledge is acquired, produced, and represented.

Each chapter provides discussions within the content areas to reveal why embodied principles, approaches, and techniques facilitate learning and should therefore be integrated into the K-12 curriculum and beyond. Realizing the continuous interactions among the learner's body, brain, mind, and environment provides a powerful mediating tool for the construction of an embodied learning curriculum, environmental design, and teaching pedagogy. Therefore, *Movement Matters* has much to offer educational practitioners, scholars, and researchers toward recognizing the untapped impact of embodied cognition as it can help students reach their full potential.

This book is organized into five major parts. The foreword, written by Lawrence Shapiro, Ph.D. (Philosophy, University of Wisconsin–Madison), explicates the foundations of the philosophy of mind and philosophy of psychology. He does this brilliantly through a compelling metaphorical description using *The Matrix* movie and its characters to unpack embodied cognition. Shapiro notes that psychologists and educators who have embraced embodied views of cognition now seek to understand how a student's gestures might indicate something about their grasp of mathematical concepts and how a teacher's gestures might in turn illuminate these concepts. He further argues that embodied cognition has inspired new and promising educational strategies (including many found in this book), which have already proven superior to the "learning-by-recipe" route.

Part I, "Philosophical and Theoretical Background," discusses the mind/body dichotomy, the foundations of cognitive psychology, and computational models of mind (cognitivism). The authors in this section address the first step in our *Translational Learning Sciences Research* (Macrine & Fugate, 2021) model by tracing the history of thinking. These chapters highlight the promise of embodied cognition for education, in which the mind and body work together to aid cognition and ultimately learning.

Part II, “Language,” applies the principles of embodied cognition in the content areas of handwriting, vocabulary acquisition, language development and comprehension, and computerized reading. This section, based on the first and second steps in *Translational Learning Sciences Research* (Macrine & Fugate, 2021), introduces literacy-based research into tools and interventions to help us to understand that both physical and imagined manipulation leads to large gains in memory and comprehension.

Part III, “STEM,” contains four chapters dedicated to mathematics and sciences. Similar to the focus of part II, our model translates STEM-based research into tools and interventions that emphasize the importance of early finger counting and manipulatives, as well as the importance of hand and body gestures in understanding physical forces.

Part IV, “Applied Technology,” contains four chapters relating the principles of embodied cognition to learning technologies developed for various digital platforms, including kinesthetically active games using sensors and motion capture, as well as those for augmented and virtual reality. In a special chapter, some of these embodied educational techniques are adapted for use with individuals with special needs. These authors translate the latest systematic efforts to convert basic research knowledge into practical applications to enhance teaching and learning.

Part V, “Social Cognition, Emotion, Mindfulness,” explores how mirror neurons within the brain serve as the biological mechanism for social connectedness and emotion, as well as how individuals with disordered sensorimotor experiences might learn differently. Finally, it elucidates an understanding of how emotion is embodied, and how emotional and mindfulness interventions benefit classroom behavior and learning.

In the conclusion, we link back to the core message of the volume: the importance of embodied approaches to teaching and learning. We reflect on the clear signals from the research to provide insights that would not have been possible had this book not been researched and written and these findings not translated and developed. For example, we show how embodied approaches can change the way we teach and learn and how they can inform curriculum development, teacher education programs, education psychology courses and textbooks, and special education. Further, we discuss how this collection serves as a useful road map and source for future educators, researchers, and scholars as they make their own connections for teaching and learning. Finally, we discuss the importance of getting this vital information into the hands of teachers and learners, educational psychologists, and curriculum designers. We hope to encourage others to investigate and explore approaches and applications to embodied learning—and the science behind it.

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I PHILOSOPHICAL AND THEORETICAL BACKGROUND

1 Embodied Cognition and Its Educational Significance

Sheila L. Macrine and Jennifer M. B. Fugate

Historically, the human mind was considered the sole source of knowing, thinking, and teaching, with the body considered both separate and inferior. Psychologically, cognition was seen as disembodiment (*res cogitans sine corpore*), in which the perceptual and motor systems were not considered relevant to understanding "central" cognitive processes (Wilson, 2002; Woodward et al., 2009). As such, classical views of cognition from psychology emphasized the storage and use of knowledge based upon mental representations (symbols), devoid of how the initial information was perceived through the body and the sensorimotor systems (Fodor, 1975, 1983; Newell & Simon, 1972; Pylyshyn, 2009; Tulving, 1983; for recent reviews, see Fugate et al., 2018; Macrine & Fugate, 2020), and separated from the brain's modal systems for sensing, action, and affect (Smith & Medin, 1981). Philosophically, the body was seen as an impediment to the mind's expansion and capabilities—an albatross levying a heavy drag on self-realization (Bordo, 1993; Macrine, 2002). This classical approach denied emotional and bodily reality altogether (Robinson & Pallasmaa, 2015), but the latest neuroscience evidence validates an embodied view of mind and its connection to the body.

Classical Views of Cognition

Since the time of Aristotle (384–322 B.C.), the body and mind were seen as separate and hierarchical in nature. Specifically, Aristotle believed that the mind ruled over the body, and reason over the emotions (Barnes, 1995). As a result, one had to discipline and dominate the body and emotions in order to free the rational mind. These assumptions informed René Descartes's (1596–1650) notions of the dichotomous nature of the mind/body separation (Ryle, 1949). He contended that the mind must be cleared, and the foundation of knowledge laid (preconceived universal truths), an idea known as foundationalism. Metaphorically, the idea was like an architect demolishing and clearing the land before building a house. In his “First Meditation,” Descartes posited that trusting perception alone (i.e., the senses to explain experience) was limiting because the senses can be deceived (Descartes, 1637/1998). For example, Descartes argued that far-away objects appeared to be quite small even though they were not actually so, and therefore our bodily senses were not reliable. Descartes insisted that the mind must be absent of any biological or social influences that might contaminate or taint true knowledge or reason. Cartesian theory held that the mind determined physical acts, and therefore volitional acts of the body must be caused by volitional acts of the mind.

Gilbert Ryle (1900–1976), the British philosopher, challenged Cartesian dualism when he suggested that sensations, thoughts, and feelings do not belong to a mental world distinct from the physical world. In fact, he called this the myth “the ghost in the machine” (Ryle, 1949). Building on this, Ryle theorized that the body and mind do cooperate, but only accidentally, with each retaining full autonomy from one another. In other words, all mental and physical activity occurs simultaneously but still separately.

Although a greatly scaled-down history, the legacy of Descartes’s dualistic theory of knowledge continues to shape modern views of knowing and learning. Foundationalism, the basis for Western epistemology, philosophy, and the sciences, still dominates educational thought. So how do we move beyond classical views of cognition to embodied cognition and an embodied approach to teaching and learning?

Education as a Result of the Classical View of Cognition

Historically, Western philosophy conceptualized the body as an instrument to be directed and a possible source of disruption to be controlled by our rational faculties (Lennon, 2019). These types of grand narratives have attempted to explain our social reality in its entirety. As a result, the mind and body separation informed the foundation of Western thinking about how knowledge is acquired and how learning occurs. In the case of psychological and educational theories, these narratives have ranged from behaviorism and stimulus-response thinking to blank slate processing, information processing, computational processing, and recently to artificial intelligence (more on this later). None of these views saw the body (or senses) as instrumental to cognition. In addition, these approaches paid little attention to the roles of learning in the affective domain. Both the teachers’ and the students’ bodies, as well as the social contexts in which learning occurs, were seen as irrelevant to the teaching-learning event (Macrine, 2002).

Constructivism emerged as an alternative, and it rescued the learner from the behaviorists' role of receiver of knowledge. However, constructivism still posited that knowledge was a product of the "individual's mind" and fashioned its mental schemas to correspond with reality or social influences. Emphasizing cognition through critical thinking left the focus of learning as purely an intellectual activity (Brookfield, 1985; see Ollis, 2012, for a review). Here, knowledge was still seen as individual in nature and based on the technical interests of the rational individual seeking control over life and the environment (Lave & Wenger, 1991). The implication for learning was that it is basically a private, individualistic matter.

The resultant constructivist pedagogical approaches took students out of the complex and dynamic life of everyday activities to sit them down in front of workbooks, skills, and drills (Newman et al., 1989). This model neglected the situated body and continued to rely on a noncontextualized, disembodied curriculum that inevitably resembled its predecessors. In fact, Matthews (1992) critiqued constructivism as the well-known metaphor "a wolf in sheep's clothing"—or to change metaphors, like the empiricists' wine served up in new wineskins. Ernst von Glasersfeld (1987, 1995), the father of radical constructivism, wrote that it is difficult to make the case for constructivism because its arguments almost always get tangled up within the old epistemological web from which constructivism desperately tried to free itself.

While psychology has been more open to progressive notions such as constructivism, social constructivism, and radical constructivism, many of these models still bare the same computational cognitive orientations. Schools, whether they are conscious of it or not, still work hard to separate the mind from the body (Macrine, 2002): Cartesian dualism is still pervasive throughout school settings. The teacher is seen as a "talking head"—a disembodied and disempowered conduit for core curriculum. These disembodied threats come in the form of rote memorization, mindless drills, and skills in preparation for standardized testing. Even now, the ramifications of our epistemological heritage continue to have quite an effect on how we conceptualize knowing, learning, and teaching.

Philosophical and Psychological Influences on Embodied Cognition

In contrast to the classical views of cognition, the famous philosopher Maurice Merleau-Ponty understood the importance of not just knowing why but *how* we gain knowledge (1962; see also O'Neill, 1974). Merleau-Ponty's (1962) notion of knowledge emphasized *I am my body*. Against Cartesian dualism, Merleau-Ponty's existential phenomenology maintained that thinking was a fully embodied event: people perceive the world first and foremost through their bodies. He argued that cognition cannot be understood without the body's engagement with the world (see also Leitan & Murray, 2014; Marshall, 2008; Merleau-Ponty & Fisher, 1965). Lather (1991) insisted that we foreground the relation between the knower and known, teacher and taught, from an embodied perspective.

In the field of psychology, John Dewey (from works between 1925–1953), echoing William James (1892), suggested that higher-order cognitive functions are adaptations generated by interactions with the world. Both James and Dewey rejected the "rational psychology" drawn from Cartesian dualism. Later, James Gibson's "ecological theory" (1979) married both phenomenological (i.e., the *subjective experience*) and naturalistic perspectives. Gibson argued that perception was direct and the environment meaningful (see Leitan & Chaffey, 2014, for a review). Consequently, Gibson suggested that there was no mind between perception and action, and that action was based in the body, supported through evolution and the environment. Gibson called these "affordances," the idea that opportunities for action are provided by a particular object or environment.

Most recently is the added idea that the brain's role is to predict incoming stimuli to exert action. Continuing these ideas, developments in robotics (see Brooks, 1991) and dynamic system theory (see Beer, 1998; Thelan & Smith, 1994) treat cognition as arising from interactions with the world. In one of the most widespread notions of the mind, Andy Clark (2013) has posited a bidirectional, iterative relationship between sensorimotor input and conceptual knowledge, such that the brain is constantly predicting what sensory and bodily information is being encountered and then using stored knowledge via feedback to refine these predictions (for a similar view, see Barrett, 2017, discussed in detail in Fugate & Wilson-Mendenhall, chapter 18 in this volume). In fact, some robotics researchers have argued that true artificial intelligence can only be achieved when robots are able to connect sensory and motor skills through a body (see Brooks, 1991; Pfeifer, 2001, 2006).

Theories of Embodied Cognition

Our current understanding of human thinking and cognition rejects Cartesian dualism in favor of embodied cognition, which grounds cognition in sensory and motor activity. As a result, cognitive psychology has undergone a theoretical shift to acknowledge that sensorimotor processing is fundamental to understanding information (Smith & Sheya, 2010).

Embodied cognition suggests that the physical body plays a significant causal role, or a physically constitutive role, in cognitive processing (see Wilson & Foglia, 2015). Some of the core principles of embodied cognition are derived from the early ideas of developmental and educational psychologists (e.g., Dewey, 1938, 1989; Kolb, 1984; Piaget, 1952, 1968; Montessori, 1969; Rogoff, 1990; Vygotsky, 1978). Early work on action-on-thinking can also be seen in sociocultural psychology (e.g., Vygotsky, 1978), activity theory (e.g., Gal'perin, 1992; Leontiev, 1978), and apprenticeship in thinking (e.g., Rogoff, 1990) and by a variety of perspectives of learning, activity, and knowledge appropriation (e.g., Brown et al., 1989; Lave & Wenger, 1991; Robbins & Aydede, 2009; Rogoff, 1990; Wilson & Foglia, 2015).

Hockey and Allen-Collinson (2009) wrote that phenomenologically "we know the world through the body, just as that body produces the world for us" (p. 117). From this perspective, experiences are always embodied and relational, and the body plays a central role in shaping our experience of the world (van Amsterdam et al., 2017). Therefore, thinking extends throughout the body and is scaffolded upon a material and social world (for corresponding views, see Bahler, 2016; Clark, 1998; Damasio, 1994; Gallagher, 2005; Gopnik, 2009; Rowlands, 2010; Sheets-Johnstone, 2011; Shapiro, 2014; Yancy et al., 2014).

Barsalou's (1999) perceptual symbols systems (PSS) was one of the first explicit, psychological theories of embodied cognition. Specifically, Barsalou stated that knowledge is reenacted (i.e., simulated) through the perceptual and sensory systems it engages (e.g., auditory, visual, motor, and somatosensory). According to PSS theory, thinking about an action evokes the same visual stimuli, motor movement, and tactile sensations that occur during the act itself (Barsalou, 2003, 2008). The experience is captured by the sensory and perceptual systems and can be later used to re-create (through simulation) the experience without the actual stimulus (i.e., when just thinking about the knowledge).

Although there are a number of theories of embodied cognition, they are all united in their emphasis on the body functioning as a "constituent of the mind," rather than secondary to it (see Leitan & Chaffey, 2014, p. 3; Shapiro, 2007). Two common themes emerge across such embodied theories. First, the body and the world (environment) are integral to form, integrate, and retrieve knowledge, and knowledge is *grounded* or *situated* in the interactions between the individual and the environment. In some versions, *grounding* represents how mental representations are understood and learned (e.g., Barsalou, 2008; Glenberg & Gallese, 2012; Lakoff & Johnson, 1999). In some cases, language is thought to be the tool that binds together individual, heterogenous instances underlying abstract concepts because direct simulation would be harder than for concrete concepts (Borghi & Binkofski, 2014; Mazzuca et al., 2017; also see Fugate & Wilson-Mendenhall, chapter 18 in this volume). In other cases, metaphors are thought to ground abstract concepts (Lakoff & Johnson, 1980). In other versions, there is no grounding necessary because there are no mental representations; rather, the individual's interaction with the environment *is* the unit of knowledge (e.g., Hutto, 2005). Second, knowledge is *simulated* (Barsalou, 1999, 2008; Gallese, 2009), such that thinking and recalling information is re-experiencing the bodily states at the time of encoding and does not represent amodal (symbolic) concepts. Although the contents of simulation are in the past, simulations occur in the present and can therefore be affected by current constraints as well.

Recently, embodied cognition has extended its reach into "4E cognition," in which cognition is not only *e*mbodied, but *e*mbedded, *e*xtended, and *e*nacted (see Gallagher as cited in Rowlands, 2010). Specifically, *embedded* refers to the fact that our bodies are situated in the environment, and our bodily capacities are geared toward current concerns and goals (i.e., affordances; see also Pouw et al., 2014). *Extended* refers to the fact that the boundaries of mind are engaged in enculturated practices, routines, societal norms, and the like. Finally, *enacted* refers to the fact that the body is self-producing and adaptive, with its own identity as it draws from the physical environment on which it depends. The body is a continually changing structure that determines its own actions on itself and its world. These assumptions bear resemblance to embedded cognition (Pouw et al., 2014), which suggests that perceptual and interactive richness "embed" a person's cognitive activity in the environment.

Today, researchers in various research areas such as developmental psychology (Thelen & Smith, 1994), biology (Maturana & Varela, 1987), language (Lakoff & Johnson, 1980), neuroscience (Chiel & Beer, 1997; Kiefer & Trumpp, 2012; Rizzolatti & Arbib, 1998), and philosophy (Clark, 1998, 1999; Varela et al., 1991) are rethinking and incorporating the role of the body in their disciplines. For instance, studies using functional magnetic resonance imaging show that motor portions of the brain re-create physical experiences when we read, see, or hear of them (Bergen, 2012). While it is understood that movement and action help to shape our perception and learning in early life, they also continue to impact the way we experience the world throughout development and into adulthood (Kontra et al., 2012).

Embodied Learning: Shifting Educational Models

As a result, embodied cognition holds promise for understanding the role of action and experience in learning contexts, as well as using action to scaffold learning in more formal educational settings later in development (Kontra et al., 2012). Derived from these principles, embodied learning constitutes a contemporary pedagogical theory of learning that emphasizes the use of the body in educational practice as well as student-teacher interaction both in and outside the classroom (Kosmas & Zaphiris, 2018; Smyrnaiou et al., 2016). Embodied learning posits that an action-to-abstraction transition includes a variety of body-based techniques (i.e., gestures, imitations, simulations, sketching, and analogical mapping) (Weisberg & Newcombe, 2017). For example, the mirror neuron system contains neurons that not only fire when we undertake an action but also when we observe others undertaking the same actions (Rizzolatti & Craighero, 2004; see Butera & Aziz-Zadeh, chapter 16 in this volume). This system appears to play a fundamental role in both action understanding and imitation; therefore, higher cognitive abilities might be dependent on the reenactment of sensory and motor representations (see also Caramazza et. al., 2014).

Alibali and Nathan (2018) have developed several principles that highlight the importance of actions as they relate to embodied learning. (1) Action matters for cognitive performance and learning. (2) Observing others' actions can activate action-based knowledge. (3) Imagining (or mentally simulating) actions can activate action-based knowledge. (4) Simulated actions are sometimes manifested in gestures and forms of representational action. They concluded that these principles, which focus on action, also have widespread implications for the Learning Sciences, including instructional design and assessment. This idea also includes the use of "manipulatives" (physical objects that can be touched and moved with the hands during problem solving and learning) (see Donovan & Alibali, chapter 10 in this volume). This also means that, as technology and digital content become more integral to learning in the classroom, designers and scientists should consider such principles when incorporating mediated content (see Trninic & Abrahamson, 2013; see Johnson-Glenberg, chapter 15 in this volume).

In terms of teaching students with learning differences, there are a number of notable adaptive embodied interventions that are available (see Tancredi et al., this volume) and also therapies for children with disabilities/delays/disorders, including autism spectrum disorder (Ollendick & King, 2000; Srinivasan & Bhat, 2013; see Davis et al., chapter 17 in this volume). Embodied approaches have also been developed to treat adults with mental illness and improve emotional well-being, and they include body-based therapies (Genosko, 2002; Michalak et al., 2012) as well as attention and disambiguation of affective states through mindfulness and increased emotional granularity (see Fugate & Wilson-Mendenhall, chapter 18 in this volume).

Because learners' bodies represent their past and present experiences and constitute educational discourses (Hunter, 2004), individuals bring their own *lived* bodies into the classroom (Hooks, 2003). Embodied learning recognizes that understanding and retention are affected by the body and sensory input. Individuals' interactions with the world impact their own motor and perceptual systems and thus will be also shaped by their culture (see Leung et al., 2011). Said another way, the cognitive structure of an individual—as defined by his or her own experiences and those supported by cultural norms and language—informs how information is first experienced as well as later simulated (Fugate et al., 2018). Specifically, Fugate et al. (2018) have suggested that this implies two things. (1) Similar actions may be encoded differently within the brains of different individuals because their perceptual and motor systems have had a different set of experiences that inform their current experiences. (2) The representation of this information may be different for individuals from different cultures, which have different priorities, rules, words, and linguistic metaphors to explain the world around them. Thus, the implication for embodied learning and teaching is that the learner needs to be seen and taught as a whole being, permitting learners to experience themselves as an integrated whole, rather than with separate mental and physical mechanisms isolated from each other (see also Stolz, 2015).

Conclusions

The link between neuroscience and education can create viable embodied applications for education. Clearly, embodied cognition and embodied learning show promise and provide a starting point to advance our understanding of how perceptual, sensorimotor, and multisensory approaches can facilitate and encourage learning. In sum, embodied cognition scientifically endorses and advances sensorimotor learning and offers potentially useful tools for educators' understanding of teaching and learning (Macrine & Fugate, 2020). Conversely, if educators remain unaware of the potential influence that embodied cognition/learning can make on educational practice, then suboptimal teaching and learning methods will prevail. As a result, we believe it is important for neuroscience and education to form effective partnerships, and that researchers, educational psychologists, teachers, and program designers consider how they can promote the principles of embodied learning in the classroom, curriculum, technology, and beyond.

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2

Embodied Concepts: Basic Mechanisms and Their Implications for Learning and Memory

Markus Kiefer, Carmen Hofmann, and Petra A. Arndt

According to Piaget's theory of cognitive development, children acquire knowledge through sensory experiences and the manipulation of objects until the age of two. After learning to use symbols (e.g., words, pictures) to represent and think about objects and events, children are thought to develop logical thinking, which is still based on concrete events between the ages of seven and eleven (Piaget, 1952). Formal logical thinking detached from sensorimotor experiences, the highest level of cognition, is assumed to develop later during adolescence. According to this theory, formal logical thinking replaces thinking based on sensory and motor processes (Inhelder & Piaget, 1958). At that stage of development, thought operations do not need to relate to concrete experiences and phenomena. The question whether this theory holds is of high relevance for the design of school lessons. At present, teachers often follow the implications of Piaget's model: in primary school, discovery learning and experiential learning activities are common instructional strategies for active learning arrangements. By contrast, in secondary schools these teaching strategies are less common. Often they are limited to active phases in natural science classes (if they occur at all).

Consider a classroom situation in which a teacher wants to introduce an unfamiliar musical instrument, a bassoon, to her or his students. She or he has several possibilities for teaching the relevant information. For instance, (1) the teacher can verbally describe the shape, the material, the sound, and the use of this musical instrument. (2) The teacher could show a movie demonstrating the physical properties, the sound, and the use of a bassoon. (3) The teacher could take the students to an orchestra where they can observe a musician playing the bassoon and can touch or play the bassoon themselves. In this case, perceptual and motor information elicited by the direct experience are the basis of knowledge building. The different methods to teach a bassoon may be differentially efficient in supporting learning. It would be therefore important to know which methods have the most beneficial effects and why (Kiefer & Trumpp, 2012).

From Amodal over Embodiment to Hybrid Theories of Conceptual Representations

Psychological and neuroscientific research provides information on the relationship between sensorimotor processes and abstract cognitive processes. At the heart of the past and the current debates is whether cognition is essentially grounded in our senses and in our actions with the environment (Markie, 2008). Traditionally, cognition is assumed to involve neurocognitive systems that are different from the perceptual or motor brain systems and code knowledge in an abstract-symbolic format, in which original modality-specific sensorimotor information is lost (Anderson, 1983; Pylyshyn, 1984; Quillian, 1969; Tyler & Moss, 2001). This resembles the stage of formal logical thinking in Piaget's classical theory (Inhelder & Piaget, 1958), as outlined earlier.

At an anatomical level, amodal conceptual representations are assumed to be held in heteromodal association cortex such as the anterior temporal (McClelland & Rogers, 2003; Rogers et al., 2004) or posterior temporal cortex (Hoffman et al., 2012), so-called semantic hubs. Although some traditional amodal theories do not deny the involvement of the sensory and motor systems in conceptual tasks, they assume that activation of modality-specific representations during language comprehension or conceptual thinking is only a concomitant process after the amodal concept has been accessed, due to imagery (Machery, 2007) or passive spreading of activation to input or output levels (Mahon, 2015).

Challenging this classic view, recent theories of embodied cognition, which are also known as "grounded" or "situated" cognition theories, have emerged in several disciplines of the cognitive sciences (Barsalou et al., 2018; Kiefer & Barsalou, 2013; Kiefer & Harpaintner, 2020; Lakoff & Johnson, 1999; Pulvermüller & Fadiga, 2010). Embodiment theories propose close links between the sensory and motor brain systems on the one hand and cognition on the other hand (Kiefer & Trumpp, 2012). Cognition and thinking is critically based on a reinstatement of external (perception) and internal states (proprioception, emotion, and introspection) as well as bodily actions that produce simulations of previous experiences. These simulations of previous sensorimotor experiences (Kiefer & Barsalou, 2013) are often unconscious but can be measured with behavioral or neuroscientific experimental techniques (Trumpp et al., 2013).

Most recent evidence suggests an interplay between modality-specific, bimodal or trimodal, multimodal and amodal semantic hub regions, giving rise to the development of so-called hybrid theories (Kiefer & Harpaintner, 2020; Kuhnke et al., 2020; Patterson & Ralph, 2016; Popp et al., 2019). Modality-specific and multimodal regions presumably represent conceptual feature content (Kuhnke et al., 2020), whereas semantic hubs code conceptual information in an overarching supramodal fashion (Binder, 2016). Most likely, a hierarchy of processing circuits (ranging from lower-level modality-specific cortex over multimodal regions up to top-level amodal areas in heteromodal cortex, indexing increasing levels of abstraction) establishes conceptual representations (Kiefer & Harpaintner, 2020; Kuhnke et al., 2020). In the next sections, we provide a comprehensive overview of the latest research on embodied cognition in several cognitive domains and discuss important implications for learning and teaching.

Embodiment of Memory for Events

Past events such as incidences associated with our last birthday are stored in episodic memory, the long-term memory system for events (Tulving, 1972). When we recall these events, not only do we recall abstract-symbolic verbal knowledge, but we also reactivate stored sensorimotor experiences collected during the initial learning episode (Engelkamp & Jahn, 2003). These reactivations of acquired sensorimotor memory traces are not epiphenomenal but are essential for memory performance.

The so-called enactment effect nicely illustrates the importance of rich sensorimotor experiences (Engelkamp & Jahn, 2003): Participants remembered a list of action verbs better when they performed the corresponding actions in the learning phase, compared with a condition when they simply read the words. Observing others who performed the action also improved subsequent memory compared with reading, but it was inferior to self-performed actions (Senkfor, et al., 2002). Neurophysiological recordings of brain activity during memory recall revealed an activation of motor areas only for self-performed actions during learning (Senkfor et al., 2002), suggesting that action representations established during word learning were reactivated and facilitated memory retrieval. Reactivations of stored experiences in modality-specific brain areas (i.e., areas specifically engaged in perception or action) during memory retrieval are not only observed for self-performed actions but also for sensory information such as vision or sound associated with the learning episode (Ranganath et al., 2004). This finding shows that episodic memory is multimodal in its essence because it is based on a reinstatement of sensory and motor experiences (Engelkamp & Jahn, 2003).

Establishing the relevant sensory and motor memory traces during learning therefore improves subsequent memory performance compared with pure verbal learning. These results suggest that teaching strategies such as (language) learning through drama, "experiments," and outdoor activities are suitable to support the building of memory by providing multimodal information (e.g., science learning; Uysal & Yavuz, 2018). Moreover, the enactment effect indicates that vocabulary training of action verbs can be improved by the corresponding movements.

Embodiment of Conceptual Memory for Objects

Concepts held in semantic long-term memory (Tulving, 1972) include the sum of our sensory and motor experiences with the environment in a categorical fashion (Kiefer & Pulvermüller, 2012). For instance, the concept "bassoon" includes the information that a bassoon has a long shape, is made of wood, produces sound, and is a wind instrument. It is an important question whether even concepts—the abstract constituents of thought—are grounded in perception and action.

Neuroimaging results (for an overview, see Kiefer & Barsalou, 2013) have provided converging evidence on the differential involvement of sensorimotor brain areas in the processing of words and concepts of different kinds (e.g., vision-related concepts versus action-related concepts). When processed, these words elicited activity in sensorimotor brain areas in a range of conceptual tasks (Hoenig et al., 2008; Simmons et al., 2005). In fact, conceptual and perceptual processing functionally and neuroanatomical overlaps in sensory brain regions: Visual recognition of words denoting objects, for which acoustic features are highly relevant (e.g., sound-related concepts such as "telephone"), ignited cell assemblies in auditory brain regions that were also activated by sound perception (Kiefer et al., 2008). Processing of action words (e.g., "to throw") elicited activity in motor areas (Hauk et al., 2004), partially overlapping with activity induced by real movements of the corresponding limb (e.g., hand-related movements).

Functional magnetic resonance imaging studies (Kuhnke et al., 2020; Popp et al., 2019), however, have indicated that not only modality-specific brain areas as defined by localizer tasks (e.g., acoustic localizer: listening to sounds; motor localizer: moving the hands) but also adjacent higher-level multimodal regions respond to concepts with a high relevance of a given feature type (e.g., acoustic or action features). Activity in both modality-specific and multimodal regions was modulated by task demands, indicating conceptual flexibility at various levels of the conceptual processing hierarchy. As already outlined at the beginning of this chapter, a hierarchy of processing circuits establishes conceptual representations (Kiefer & Harpaintner, 2020; Kuhnke et al., 2020;

Popp et al., 2019). These findings thus support hybrid models of conceptual representations combining assumptions of modal embodiment theories with those of amodal theories (Kiefer & Pulvermüller, 2012; Patterson & Ralph, 2016).

Conceptual memory traces in sensorimotor areas are established through the learning-based formation of cortical cell assemblies as a direct consequence of the experience with the referent. One line of evidence comes from training studies on the experience-dependent acquisition of concepts for novel objects (T. W. James & Gauthier, 2003; Kiefer et al., 2007). For instance, human participants learned concepts of novel objects ("nobjects") under different training conditions (Kiefer et al., 2007): the participants either made an action pantomime toward a detail feature of the novel object, which signaled a specific object function, or pointed to it. During the test, only for the pantomime group—in which a meaningful action was performed toward the object during training—was there early activation in frontal motor regions and later activation in occipitoparietal visuomotor regions during conceptual processing, indicating that action representations essentially constitute the concept. In the pointing group, in which the action during training was not meaningfully related to the object, this sensorimotor activity was absent, suggesting that concepts were not grounded in action.

The second line of evidence comes from studies investigating experience-dependent formation of conceptual representations in experts with real objects. For instance, only professional musicians, but not musical laypersons, activate the auditory association cortex when accessing conceptual knowledge about musical instruments (Hoenig et al., 2011). Together with similar expertise studies (Beilock et al., 2008; Lyons et al., 2010), these findings confirm that the grounding of concepts in the sensorimotor circuits of the brain is the result of repeated meaningful interactions with the referent. If this experience is lacking, concepts are less rich and are mainly based on verbal associations (Solomon & Barsalou, 2004). In fact, we found that deaf individuals, who could not rely on the auditory input channel since early childhood, recruited language brain systems more strongly than hearing individuals (Trumpp & Kiefer, 2018). This study also showed that deaf individuals compensated for the loss of the auditory channel by additional recruitment of visual and motor areas.

Returning to the bassoon example, when confronted with the name "bassoon," for instance, a musical layperson or a deaf individual may be able to retrieve other words typically co-occurring with the word "bassoon," such as "musical instrument," "orchestra," or "violin," without having a clear grasp what a bassoon really is or how it sounds. In contrast, musical experts have profound experience and knowledge about the shape of a bassoon, its sound, and the actions need to play this instrument. This notion of experience-dependent plasticity of conceptual representation supports teaching approaches like scenic learning in foreign language teaching, in which vocabulary training is accompanied by meaningful gestures and movements not only for action word but also for nouns (Macedonia & Klimesch, 2014).

Embodiment of Conceptual Memory for Numbers

Although the embodiment of object concepts may be intuitive to some extent, it is less obvious how abstract concepts such as numbers, which do not have a clear physical referent, are grounded in perception and action. Nevertheless, several lines of evidence show that processing number concepts (e.g., knowing that 6 is greater than 4) involves the sensorimotor systems similar to concrete object concepts.

First, accessing number magnitude depends on a mental number line, which resembles visuospatial representations (Dehaene, 1992). Behavioral number comparison experiments (e.g., deciding which digit is larger, 6 or 2) provide objective evidence for the existence of an analogue mental number line that has a logarithmic scale similar to the mental representation of the size or intensity of sensory stimuli (Nieder, 2005). Furthermore, neuroimaging studies consistently have shown that number magnitude is represented in a parietal area (intraparietal sulcus) that is also involved in processing space (Nieder, 2005).

Second, in addition to visuospatial representation, numbers are grounded in the motor system, particularly in hand actions (Lindemann et al., 2007). Most impressively, finger counting systems used in childhood to learn numbers still play a role in adults when they process numbers. Intercultural studies have shown that reaction times in a number comparison experiment are strongly influenced by the finger-counting habits typically used in a given culture (Domahs et al., 2010). Only for German participants, who use unimanual finger counting habits for numbers up to five and bimanual habits for numbers greater than five, were number comparisons slower when they involved numbers both below and above five (i.e., numbers that require one versus two hands in the German finger-counting system). In Chinese participants, who use a unimanual symbolic finger counting system for these numbers, this effect was absent. In line with developmental studies demonstrating the importance of finger recognition in childhood for later arithmetic abilities (Noel, 2005), this study showed that fairly abstract number concepts are at least partially rooted in our motor experiences. In line with this documented association between numbers and finger counting, enhanced activity in the motor cortex was observed when number concepts were processed (Tschentscher et al., 2012).

Hence, number concepts appear to be embodied in both visuospatial and action-related representations. Explicitly training children in finger counting as well as in spatial analogues of number magnitude accelerates learning numbers and has beneficial effects on subsequent mathematical performance even in students' later school or professional career (see Fischer et al., 2011).

Embodiment of Memory for Abstract Concepts

By definition, abstract concepts do not refer to physical objects that can be directly experienced by the senses. The representation of abstract concepts, such as abstract ideas or scientific theories, imposes challenges for all classes of theories of conceptual representation (see also Dove, 2016). Abstract concepts are more complex and ambiguous than concrete concepts because they apply to rather heterogeneous situations (Barsalou & Wiemer-Hastings, 2005; Hoffman et al., 2013). Therefore, all theories have to deal with a high degree of conceptual flexibility. Abstract concepts are a particular challenge for embodied cognition theories because at first glance it is hard to imagine how concepts without a referent that can be perceived or acted on could be grounded in the sensory and motor brain systems (Dove, 2009, 2016).

Past research was dominated for a long time by the view that abstract concepts require amodal, symbolic (Mahon & Caramazza, 2009), or verbal representations (Paivio, 1986). In Paivio's dual coding theory (1986), abstract concepts were thought to be stored in a verbal-symbolic code, whereas concrete concepts relied on both a visual imaginary and a verbal-symbolic code.

In the recent years, however, in order to account for the representation of abstract concepts, embodied cognition theories have been refined. We and others have suggested that abstract concepts might be grounded not only in the perception of external events such as situations, but also in the introspection of internal mental states and in mentalizing social constellations (Barsalou & Wiemer-Hastings, 2005; Borghi & Binkofski, 2014; Harpaintner et al., 2018; Kiefer & Barsalou, 2013) or in processing affective states (Kousta et al., 2011).

Refined embodied cognition theories have been confirmed by several lines of research that indicate that abstract concepts depend not only on the verbal system but also on a variety of modal systems, including perception, action, emotion, and introspection (for reviews, see Borghi et al., 2017; Kiefer & Harpaintner, 2020). A property listing study (Harpaintner et al., 2018) revealed that participants generated a substantial proportion of introspective, emotional, and social properties in addition to verbal associations. In terms of quantity, however, sensory and motor properties played the most crucial role in this study. The broad diversity in the participants' listings was consistent with refined grounded cognition theories, showing that the semantic content of abstract concepts includes various semantic features. These results also suggest that only one relatively small subgroup of abstract concepts is predominantly related to verbal associations.

In line with this property listing study, neuroimaging studies have identified activity areas related to emotions (Vigliocco et al., 2014), mental states (Wilson-Mendenhall et al., 2013), and social interactions (Wilson-Mendenhall et al., 2013) when abstract concepts are processed. Furthermore, similar to concrete concepts, subgroups of abstract concepts have been shown to activate visual and motor areas also involved in perception and action (Harpaintner et al., 2020). For example, abstract physical concepts related to periodicity (e.g., "frequency") activated postcentral and parietal brain regions—regions found to be active when performing rhythmic movements (Mason & Just, 2016).

Hence, in contrast to Piaget's view that scientific or mathematical concepts essentially build upon abstract formal logical reasoning (Inhelder & Piaget, 1958), the findings reviewed here show that even fairly abstract concepts are grounded in modal systems including emotions, introspection, perception, and action. We assume that such a grounding in experiences is necessary for a deep understanding of abstract concepts, whereas knowledge is superficial when only based on verbal instruction. We therefore propose that abstract concepts should be taught by providing learners with meaningful visualizations or movements.

Embodiment of Reading and Writing

Writing is a manual sensorimotor skill that requires the acquisition and storage of complex motor programs. For reading, its grounding in the sensorimotor systems is less obvious, because reading is typically considered to be purely perceptual (e.g., McClelland & Rumelhart, 1981). However, embodiment theory predicts that reading is influenced by writing techniques because the motor programs and sensory experiences during writing (e.g., forming specific letters and words with a pen) are assumed to be implicitly activated during reading. As a consequence, our habitual writing techniques should affect reading performance.

It is particularly important to consider this possible relation between reading and writing because nowadays digital writing devices associated with the use of mobile phones, tablets, or computers have frequently replaced writing by hand (for an overview, see Kiefer & Velay, 2016). The sensorimotor experiences during handwriting (haptic, motor, visual, etc.) are quite different from those during typewriting or mouse clicking on digital devices. In particular, handwriting requires carefully reproducing the shape of each letter, whereas in typewriting no such graphomotor component is present. Given that modern children may learn writing by typing on a computer or mobile phone long before they master handwriting, it is important to know how this dramatic change in writing habits affects reading performance (Mangen & Balsvik, 2016).

Consistent with embodiment theory, several training studies in preschool children and adults have shown that handwriting training of new letters gave rise to a better letter recognition in a subsequent test than typing training (e.g., Longcamp et al., 2005). This demonstrates that handwriting, which links rich sensorimotor representations to perceptual letter shapes, improves subsequent letter reading performance compared with typewriting. In line with this interpretation, neuroimaging studies showed that visual recognition of letters only activated motor regions of the brain when letters were trained by handwriting, but not when they were trained by typewriting (K. H. James & Engelhardt, 2012). The authors confirmed the assumption that sensorimotor experiences must be meaningfully related to the learning target (here, shaping a letter by writing versus pressing a key associated with a letter) to result in stronger sensorimotor memory traces that facilitate learning.

Although several behavioral and neuroimaging intervention studies seem to suggest a superiority of handwriting training over typing training on subsequent reading and writing performance in young children, other evidence has been mixed. Improved letter recognition after handwriting training compared with typing training was not always replicated (Kiefer et al., 2015). Unfortunately, the effects at the word level are also heterogeneous: the superiority of handwriting over typing training on word writing performance (Cunningham & Stanovich, 1990; Kiefer et al., 2015) was not found in other studies (Ouellette & Tims, 2014; Vaughn et al., 1992).

Mayer and colleagues (2020) therefore examined the influence of a writing tool on the acquisition of literacy skills at the letter and word level with various tests in a large sample of kindergarten children ($n = 147$). Using closely matched letter learning games, children were trained with sixteen letters by handwriting with a pencil on a sheet of paper, by writing with a stylus on a tablet computer, or by typing letters using a virtual keyboard on a tablet across seven weeks. Training using a stylus on a touch screen was an interesting comparison condition for traditional handwriting because the slippery surface of a touch screen had lower friction than paper and thus increased difficulty of motor control. Visuospatial skills were also assessed to test whether the different training regimens affected cognitive domains other than written language. Children of the pencil group showed superior performance in letter recognition and improved visuospatial skills compared with keyboard training. Keyboard training, however, resulted in superior performance in word writing and reading compared with handwriting training with a stylus on the tablet, but not compared with the pencil group.

Our results suggest that handwriting with a pencil fosters acquisition of letter knowledge and improves visuospatial skills compared with keyboarding. At least given the current technological state, writing with a stylus on a touch screen seems to be the least favorable writing tool, possibly because of the increased demands on motor control. Writing training with a stylus on a tablet led to inferior reading and writing performance at the word level compared with keyboarding. At the same time, the beneficial effects of handwriting training on letter recognition and visuospatial skills were less pronounced compared with writing with a pencil.

Conclusion

The role of Piaget's theory in the classroom has been discussed since the 1960s (Benz et al., 2015). The reception of this theory contributed substantially to the abandonment of the assumption that children's minds are qualitatively similar to adult minds and work in a similar manner (Smith, 1987). This led to changes in school curricula. More active, self-regulated learning phases were integrated into the lessons. Unfortunately, this important contribution to improving the quality of teaching was limited to preschool and primary school. Based on Piaget's stage model, secondary school students acquire knowledge on the basis of formal cognitive operations (i.e., in the way that adults subjectively perceive themselves). Subjective self-perception, however, does not correspond to current research findings.

According to the latest research reviewed here, cognition is grounded in perception and action, and even the most complex and abstract thoughts are sense-based and not abstract-symbolic. There are examples from many cognitive domains showing that *appropriate* sensorimotor experiences are necessary for human cognition to develop at the highest level. Therefore, embodied cognition theory is naturally highly relevant for many issues associated with education (Kiefer & Trumpp, 2012; O'Loughlin, 2006). Embodied cognition theory highlights the relevance of experiential interactions with our environment during learning, resulting in more endurable and—perhaps most important—richer knowledge. These experiences frequently include perception and action but may also reflect introspection of emotional and other mental states.

Returning the example of learning a bassoon at the beginning, according to a symbolic view of cognition it would be sufficient for the teacher to verbally describe aspects such as the shape, the sound, and the material of a bassoon in a written text, perhaps complemented by a picture. A direct experience with the object would not be necessary. According to embodiment theories, rich knowledge about the unfamiliar bassoon can only be acquired when the students can see, hear, touch, and act on the bassoon. A pure verbal description should result in impoverished, less durable knowledge. As human cognition is the basis for thought, language, and action, rich embodied knowledge about our physical and social world is highly important for the developing mind, educational success, and thus for the functioning of our society.

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3

Embodied, Enactive Education: Conservative versus Radical Approaches

Daniel D. Hutto and Dor Abrahamson

E-approaches to cognition, which have been developed over recent decades, challenge the mainstream representational-cum-computational approach, offering us an alternative understanding of cognition. Yet fundamental differences in philosophical outlook divide the more conservative and radical branches of the E-family. This chapter introduces the core assumptions of E-approaches to cognition and details in which ways E-theorists divide into more conversative and more radical camps.

Bracketing questions about how to decide between these options and other challenges to E-approaches, this chapter instead focuses on articulating possible practical outcomes for educators should they come to accept either of these E-approaches to cognition. Taking an imaginative leap, this chapter asks the following question: Assuming one has adopted either a more conservative or more radical E-framework, how would that choice matter to one's thinking about educational research and practice?

E-Cognition: The Conservative-Radical Spectrum

When it comes to thinking about mind and cognition, "E" is for embodied, enactive, ecological, embedded, extended, or extensive. Under the E-umbrella one finds many different and diverse approaches for thinking about the nature of mind and cognition; certainly not all of these approaches are in perfect agreement. For this reason, it is perhaps best to think of E-approaches as forming a family—a family in which some members get along better with others, and, as in some families, some members do not get along with certain others at all.[1] Yet even although—at least to date—there has yet to emerge one E to rule them all, it is fair to say that even if this family of views is not established in the sense of being fully unified, it is undeniably an emerging force that must be reckoned with by mainstream Western philosophy of mind and cognitive science.

A longstanding tradition in Western thought regards the mind as fundamentally distinct from the body. This is still very much the dominant view in mainstream analytic philosophy of mind and cognitive science, which tends to accept, by default, that the primary work of minds is to represent the world and to reason about it by manipulating said representations. In its classic cognitivist guise, the core assumption of the mainstream representational-cum-computational theories of mind is that intelligence resides wholly and solely inside us in the form of brain-based, information-driven processes.

New evidence puts this mainstream cognitivism under pressure in ways that cannot be ignored, not even by those most wedded to its mindset. Goldman (2012) directs our attention to a large swathe of empirical findings that provide "substantial evidence in support of the pervasive occurrence of embodied cognition" (Goldman, 2012, p. 80). On this long list of E-friendly experimental findings, we find evidence for the use of circuits associated with motor control functions in higher-level language comprehension tasks (Pulvermuller, 2005); the reuse of motor control circuits for memory (Casasanto & Dijkstra, 2010); the reuse of circuits that mediate spatial cognition for a variety of higher-order cognitive tasks (e.g., the use of spatial cognition for numerical cognition; Andres et al., 2007; Hubbard et al., 2005); mirroring phenomena, including not only motor mirroring but also the mirroring of emotions and sensations (Keysers et al., 2010; Rizzolatti et al., 1996; Rizzolatti & Sinigaglia, 2010); and sensitivity to the perceiver's own bodily states when estimating properties of the distal environment (Proffitt, 2008).

Focusing on empirical results of direct relevance to educational research, Shapiro and Stolz (2019) reach a similar conclusion, reporting that:

> *Recent findings* from research literature on learning and cognition from a diverse array of discipline areas, such as philosophy, psychology, linguistics, neuroscience, and computer science, *have contributed to the view that traditional cognitivist accounts of the mind should be challenged because they exclude the close relationship that exists* between *mind and body that is more profound than initially considered.* (p. 20, emphases added)

One way or another, any credible theory of mind must accommodate these kinds of empirical findings that reveal cognition is—in some centrally important respects—connected, and sensitive, to facts of embodiment.

There is a spectrum of possible ways to accommodate these findings in the theoretical space. At the conservative end of the spectrum, we find adjusted accounts of cognition that seek to make only minimal revisions to classically cognitivist views of cognition (Alsmith & de Vignemont, 2012; Gallese & Sinigaglia, 2011; Goldman, 2012). These conservative E-accounts of cognition (or CEC for short) attempt to accommodate recent findings about the role of embodiment in cognition while still conceiving of cognition as wholly representational and entirely brain bound. Theories of the CEC stripe posit mental representations with special formats that represent features of the body, holding that representations of this special kind play a much larger and more fundamental role in cognition than was previously supposed. Importantly, though advertised as E-cognition theories, accounts of this kind assume that the real work of cognition is still done essentially by manipulating mental representations in the brain.

Slightly more daring CEC theories assume that special kinds of action-oriented and sometimes extraneural representations play a part in cognitive activity, helping to drive and steer dynamic and extended cognitive processes (Clark, 1997, 2008b, 2016). Action-oriented representations are hypothesized to be content-bearing states or processes whose functional role is to indicate the presence of, and to sometimes "stand in" for, states of affairs in order to guide and direct specific kinds of action. What makes action-oriented representations interestingly different from the classic cognitivist conception of representations is that the vehicles of the former are not assumed to be always neural and brain bound. Rather, it is assumed that cognitive vehicles and processes can, at least in some cases, reach across brain, body, and environment. CEC approaches of this slightly less conservative stripe are able to put appropriate emphasis on "the profound contributions that embodiment and embedding make" (Clark, 2008a, p. 45).

At the more revolutionary end of the spectrum we find E-approaches that seek to replace classic cognitivist assumptions, root and branch (for a discussion, see Shapiro, 2011). The most radical E-accounts of cognition (or REC for short) characterize cognition, constitutively, as a kind of organismic activity that occurs in the form of sensitive interactions stretching across the brain, body, and environment (Di Paolo et al., 2017; Gallagher, 2005, 2017; Hutto & Myin, 2013, 2017; Thompson, 2007).

The distinguishing feature of REC accounts is their full-fledged opposition to the mainstream view that cognition essentially involves the collection and transformation of information in order to represent the world. Seeking to move away from the idea that the work of minds is always that of representing and computing, these approaches fundamentally challenge accounts of cognition that "take representation as their central notion" (Varela et al., 1991, p. 172).

The radical arm of the E-cognition movement began to be taken seriously by contemporary Western philosophers of mind and cognitive science in the early 1990s, as a consequence of the publication of a landmark book: *The Embodied Mind* by Varela et al. (1991). One major source of inspiration for radicals within the E-family comes from Buddhist thought and philosophy, as introduced in Varela et al. (1991).[2] There have been fruitful conversations between

Buddhist and Western traditions of philosophy of mind precisely because, although both have a dedicated interest, each for the most part approaches these topics from very different angles. This is most evident if one compares Buddhist thinking with the tenets of mainstream classic cognitivism. Simply put, these schools of thought think radically differently, and think radically different things about thinking.

It is not just Buddhism but other ancient Asian traditions of thought as well that embrace something akin to REC approaches to the mind. For example, Ilundáin-Agurruza (2016) has explored points of connection and overlap between radical enactivism and Japanese *dō*—practices that nurture self-cultivation, emotional attunement, and highly skilled performance (e.g., *kendo*—way of the sword). The most discerning reflections on expert performance, which are still used to inform these practices, regard it as requiring a state of mind literally "no mind"—a Zen expression meaning the mind without mind, known as *mushin* in Japanese and *wuxin* (無心) in Chinese.

For example, Slote (2015) claimed that Asian conceptions of mind can serve to correct the "exceedingly intellectualistic" tendencies of Western thought. It would be a mistake, however, to contrast East Asian with Western philosophy in an undifferentiated, wholesale manner. Such an exaggerated contrast misses important nuances. For one thing, this would wrongly depict Western philosophy as being entirely homogenous with respect to the conceptions of mind and cognition that it embraces. There are strands within Western thinking—such as the phenomenological and American pragmatist traditions of thought—that also lend support and succor to REC approaches. It is no accident that Varela et al. (1991) align their project with that of classic thinkers in the phenomenological tradition, including Husserl (1931/1988), Merleau-Ponty (1945/1962), and Sartre (1943/1956). Many contemporary E-theorists continued that work, renovating ideas from the phenomenological tradition and connecting them directly with current theorizing in the cognitive sciences (Gallagher, 2005, Gallagher & Zahavi, 2008).

The same goes for the American pragmatist tradition. Thus, as Gallagher and Lindgren (2015) observe, the pioneers of REC approaches "could have easily drawn on the work of John Dewey and other pragmatists. Indeed, long before Varela et al. (1991), Dewey (1896) clearly characterized what has become known as enactivism" (p. 392, see also Dewey, 1922). REC approaches gain further support from other traditions and frameworks of a more scientific bent, such as ecological psychology (Gibson, 1979), developments in robotics (Brooks, 1991), and dynamical systems theory (Beer, 1998; Thelan & Smith, 1994).

Fundamental differences in philosophical outlook clearly divide the more conservative and radical branches of the E-family. Yet despite this, when taken as a whole, those on both sides of the divide agree that “the emerging interdisciplinary research agenda of embodied cognition contains fertile ground whose surface has, to date, merely been scratched” (Shapiro & Stolz, 2019, p. 21).

E-Lessons for Educators

Exploring and developing E-approaches is undeniably important for understanding cognition. That being the case, it follows that education research needs to take serious stock of these developments because questions of how to educate cannot be kept apart from the best thinking about how we think and learn.[3] The next section touches on other empirical findings in the E-cognition domain that lend credence to Shapiro and Stolz’s (2019) claim that “the emerging research agenda of embodied cognition has much to offer educational practitioners, researchers, and/or policy-makers” (p. 34). Notably, despite their evident optimism about the value of E-approaches for education, these authors are cautious about how swiftly and easily this work will be taken up by educationalists.

Citing the alleged “newness” of E-approaches to cognition, Shapiro and Stolz propose that their encouragement of teachers to acquaint themselves with such research “ought best to be construed as a challenge and a clarion call” (2019, p. 33). Although it is true that E-approaches will likely have an uphill battle in gaining acceptance from those working in mainstream educational theory and practice in the West, the anticipated struggle cannot be put down to the “newness” of E-approaches to cognition.[4] Rather the true source of intellectual resistance to such views derives from the fact that classic cognitivist conceptions of cognition not only dominate much Western philosophy of mind and cognitive science but also infuse and inform the great bulk of ordinary and professional thought inside and outside the academy in the West.[5]

For our purposes, let’s bracket the question of how to deal with the philosophical barriers that may, for some, block the acceptance of E-approaches. Focusing more directly on possible practical outcomes, the next section takes an imaginative leap and asks a different kind of *how* question: Assuming one has adopted either a more conservative or more radical E-framework, how would that choice matter to one’s thinking about educational research and practice?[6]

Conservative and Radical Thinking about Education

E-thinking about cognition creates new possibilities to consider for those in the business of improving education practices. As Shapiro and Stolz (2019) observe, “there is considerable potential for further research and enough existing literature to suggest new ways to think about instruction and classroom design" (p. 34).

As noted in the previous section, one way or another, researchers must take seriously the empirical findings that reveal the extent to which cognition is sensitive to E-factors. Yet how one understands the relevance of those findings and how they might shape educational theory and practice is nonaccidentally tied to one's philosophical outlook about cognition and where it sits on the conservative-radical spectrum.

Exemplary Embodied Learning Techniques

To get a sense of the importance these outlooks can have to thinking about education, it is useful to consider some high-profile cases. There have been recent experimental attempts to explore the possible advantages of using enactive metaphors for educational gain. Unlike the standard use of so-called disembodied or static metaphors (those that map a source onto a target domain by means of words, diagrams, and models), enactive metaphors involve the learner in full-bodied active engagements—embodied engagements that require learners to move "in a prescribed way or play-acting a specified process" (Gallagher & Lindgren, 2015, p. 398).

Exemplifying the way such enactive metaphors might be used in the domain of teaching science, Gallagher and Lindgren (2015) cite a case in which students are asked to "metaphorically identify with an asteroid and act out its movement in a planetary system in order to learn from their own kinesthetic feedback about the principles of gravity" (p. 398) (see also Megowan-Romanowitz, chapter 11 in this volume; Vierya & Vierya, chapter 14 in this volume).[7]

There is also longstanding research into the potential that gesturing has for improving mathematical education and performance. For over two decades, philosophers and cognitive scientists have labored to understand the implications of Susan Goldin-Meadow's discovery of a correlation between gesture and enhanced mathematical performance (Church & Goldin-Meadow, 1986; Goldin-Meadow et al, 1999, 2001; McNeill, 1992; see also Schenck et al., chapter 9 in this volume). These findings are of special import when supported by recent research, such as that conducted by Wagner-Cook et al. (2017) that shows it is gestures themselves and not their accompanying nonverbal behaviors that facilitate mathematical learning.

Alibali and Nathan (2012) have begun to investigate the educational value that may be conferred by the use of different kinds of gestures. This is important since the gestures under scrutiny in educational contexts are not merely those in the familiar playbook used for conventional communication. Rather, they include pointing gestures, iconic gestures (using body parts, say, one's fingers to create a circle), and metaphoric gestures (such as using one's arms to create circular motions indicating "repetition") (see also Marquardt Donovan & Alibali, chapter 10 in this volume). In an experiment involving college students who were asked to prove a mathematical conjecture, Walkington et al. (2014) discovered that students who used dynamic gestures (compared with those who used no gestures or only static, depictive gestures of an iconic sort) were more successful, helping them achieve the correct outcome 63.6 percent of the time (see also Schenck et al., chapter 9 in this volume).

Understanding Embodied, Enactive Learning

These exciting findings raise deeper philosophical questions: Does such embodied activity convey information or content directly to the centers of cognition by bodily routes?[8] Or does it simply lighten the cognitive load, freeing up our centers for cognition to do their work better and quicker? Or is it a way of directly getting a grip on the relevant concepts? Might such embodied activity in of itself constitute direct cognitive gains?

These results can be thought of, most cautiously and conservatively, as showing that embodied activity correlates with certain educational benefits. Or, a bit more bravely, that it is causally producing said benefits. Or, much more radically, that it is actually constitutive of such benefits. It is likely that one's tendency to regard this evidence through a more conservative or more radical lens will correlate with the philosophical framework one adopts for thinking about cognition.

When it comes to thinking about cognition, those at the most conservative end of the spectrum will be inclined to interpret these findings as revealing that embodied activity noncognitively scaffolds tasks by reducing their cognitive load and freeing up properly cognitive resources. Even those who are a bit less conservative in their views about cognition will only be inclined to think that embodied activity at best shapes or contributes to cognition indirectly. Thus, they might think such activity makes a difference: to noncognitive aspects of cognitive processes, or to the way relevant information is formatted or encoded, or by supplying additional or different kinds of information.

There have been recent explanatory attempts, very much in the conservative vein, to understand how engaged activity of the sort Gallagher and Lindgren (2015) describe as "enacting metaphors" might boost educational performance. Kontra et al. (2015) proposed that the learning of scientific concepts such as torque and angular momentum is "aided by activation of sensorimotor brain systems that *add kinetic detail and meaning* to students' thinking" (p. 1, emphasis added). Similarly, Hayes and Kraemer (2017) have speculated that we will understand these educational gains once we understand "how *body-centered* *information, as computed in sensorimotor brain regions* and visuomotor association cortex can form a useful foundation upon which to build an understanding of abstract scientific concepts" (p. 1, emphasis added).

Church and Goldin-Meadow's (1986) also provide a conservative explanation to account for the discordance and concordance that can arise between gestures and speech acts. In describing this approach, Shapiro and Stolz (2019) write,

> In these cases, *the body becomes a conveyer of information* that *might be used to supplement or replace the information* provided by symbolic constructions of the sort more standardly associated with educational instruction, that is, words or writing on a board. (p. 29, emphases added)

It is easy to see a similar CEC line of thinking at work when Shapiro and Stolz (2019) suggest that it may be that certain kinds of gestures might be merely indicating a student's underlying conceptual understanding, or lack thereof. For example, as they put it, it may be that those "who display static gestures are *merely* signaling an existing . . . conceptual misunderstanding" (p. 32).

Those who adopt a REC framework put a very different spin on the evidence, making room for the possibility that nonsymbolic, nonconceptual embodied activity is constitutive, and not merely indicative, of certain kind of competence or knowledge. As such, embodied interactions with specific kinds of phenomena would qualify as varieties of knowledge and competence in their own right.

In thinking of certain embodied activities as constitutively intelligent, REC accounts can tap into a longstanding philosophical tradition in which intelligent performances are not explained in terms of "underlying, rationalising knowledge enabling the competence" (Wright, 2007, p. 498). Intelligent embodied engagements can be conceived of as structured doings that "make up a structured pattern of dynamic, bodily interaction with the environment that *exhibits* intelligence" (Hasselberger, 2018, p. 455, emphasis added).

To illustrate the point, consider the innovative work that is being done with mathematics imagery trainers, or MITs (see also Flood et al., chapter 12 in this volume, and Tancredi et al., chapter 13 in this volume).[9] MITs use natural user interface systems that enable children to engage in tasks that initially do not demand any proficiency with mathematical symbols at all, only sensorimotor behaviors such as moving (virtual) objects in order to satisfy some task condition. Once they have solved the set problem, the students are offered mathematical tools to enhance their interactions. The students adopt these tools because they recognize in them potential utilities for enhancing their actions. But in so doing the students shift into quantitative forms of reasoning about their own actions.

These innovative educational devices focus on giving students opportunities for nonsymbolic interactions with mathematical phenomena. MITs have been designed specifically to allow students to "experience first, signify later" (Abrahamson, 2015a, 2015b; see also Hutto et al., 2015; Hutto & Sánchez-García, 2015). Importantly, MITs enable children to engage in tasks that initially do not demand any proficiency with mathematical symbols at all but rely only on their engaging in embodied ways with the interface (e.g., moving virtual objects so as to satisfy specific task conditions).

In other words, MITs allow users to get a nonsymbolic, embodied grip on mathematical phenomena (Abrahamson, 2020). They are designed so that specific and mathematically relevant sensorimotor patterns arise while students use them to solve set tasks, such as keeping a screen green, which can only be achieved if the participant moves their body in conformity to a mathematical rule. Moving in accord with these patterns is novel for the student; as they explore what it takes to solve the task, they develop and demonstrate their competence in mastering the relevant norms in an embodied, enactive manner (for more on MITs, see Tancredi et al., chapter 13 in this volume; for a mathematics imagery trainer for proportion [MITp] schematic map, see Flood et al., chapter 12 in this volume).[10]

The REC slogan with respect to nonsymbolic embodied educational activity of this sort is not "stop thinking and start doing" but "starting thinking by doing." Or, as Dennett (2017) would have it, REC embraces the idea that "competence without comprehension is nature's way" (p. 84). Viewing these phenomena through the REC lens, one might be inclined to follow Glenberg (2008) in concluding that "all of these studies point to the same conclusion: Mathematics is not the cognitive manipulation of abstract symbols by rules" (p. 359). That conclusion, however, does not appear to be supported by the evidence. It is much safer to conclude that mathematics is "not only" the manipulation of abstract symbols by rules.

To provide a complete REC account of mathematical cognition requires explaining how it is possible that symbolically based concepts can be constructed and emerge from nonsymbolic embodied activity—without surrendering the idea that the content of mathematical propositions and the rules of mathematics are strongly objective. A fully satisfying account of mathematical cognition of this kind will need to make sense of its embodied, nonconceptual, nonsymbolic varieties as well as those that are symbol-involving. It will also need to provide workable explanations of how these two forms of mathematical cognition interrelate and interact despite having special features that strongly distinguish them.

In other words, a complete REC account of mathematical cognition needs to accommodate both its nonconceptual, nonsymbolic and symbolic forms.[11] This can be achieved if we assume that basic mathematical performances are not best explained in terms of learners already grasping the content of a set of rules. Instead, following REC, we need to embrace the view that, in general, cognizing is a matter of embodied engagements that enable us to get "a *grip* on the *patterns that matter* for the *interactions that matter*" (Clark, 2016, p. 292).

With this in mind, and taking a leaf out of Malafouris's material engagement theory (2013), we can think of symbols as special objects that we learn to manipulate by means of mastering public practices in accord with special norms and rules. Accordingly, "[mathematical symbols] are not an accomplishment of the [human] brain, they are an opportunity for the [human] brain—that is an opportunity for active material engagement" (Malafouris, 2013, p. 169, with edits). Moreover, the knowledge of how to use such symbols does not come from anything like an instructive prior intention, rather "the [mathematical] intention is constituted, at least partially, by [how we engage with] the [symbols themselves]" (Malafouris, 2013, pp. 173–174, with edits).

A fully detailed and satisfactory theory of mathematical cognition will require detailed accounts of the various forms and norms of mathematical cognition, as well as their origins in practices that emerged in human prehistory and those that now shape individual development and acquisition of mathematical competence (see Hutto & Satne, 2015).

REC approaches do not regard embodied activity of the sort under scrutiny here, whether purely embodied or symbol-involving, as merely instrumental—as serving, for example, only as a different sort of bodily-based supply chain for information that is to be processed by brain-based computations over mental representations.[12]

The Future of Enactive, Embodied Education

The foregoing analysis reveals the potential for fruitful alliances between philosophers working in the domain of E-cognition and educational researchers. The cross-disciplinary work of philosophers and educational scientists and practitioners can be mutually beneficial.

Philosophers gain from analyzing empirical studies that require them to think differently about the nature of cognition. Educational scientists, practitioners, and policy-makers gain by having a deeper understanding of the different philosophical ways of accommodating such findings. Knowing about those various possibilities can help them when it comes to evaluating educational activities and tools and their potential to improve teaching practice by enabling educators to do things differently.

A positive outcome of such collaborations would be for policy-makers to recognize the potential of implementing paradigms from empirical-oriented philosophy and learning sciences in the service of educational institutions. As the examples and analysis provided the previous sections demonstrate, there is potential to break new ground in educational research, practice, and policy by attending to the available evidence about cognition and considering it through the various E-frameworks we have described (see Abrahamson et al., in press).

The observations of this chapter should encourage philosophers and educators to join forces in investigating and refining our understanding of what E-approaches to cognition have to offer to teaching, and—on that basis—to cooperate in thinking about special educational tools and practices that may someday become mainstays of the regular curriculum.

Notes

1. For a detailed overview of the history and differences between E-approaches and an update on the emerging debates within and beyond this family of views, one could hardly do better than to look at Newen et al.'s *The Oxford Handbook of 4E Cognition* (2018).

2. As Thompson remarks in a recent interview, "I think it's fair to say it was the first book that related Buddhist philosophy to cognitive science, the scientific study of the mind, and the Western philosophy of mind" (Littlefair, 2020).

3. Or, to put the point in conditional, one could say, along with Glenberg (2008), "If embodied approaches to cognition are on the right track, then they should provide key insights into educational processes" (p. 370).

4. The struggle for acceptance that E-approaches are likely to face is highlighted by the mere fact that the entire family of E-views is deemed to have to prove itself against a reigning champion. We can see this assumption at work in the very idea that E-cognition has a kind of "upstart status" (Shapiro & Stolz 2019, p. 33), and that it is thought to be, despite its long history, "still in its infancy" (Shapiro & Stolz, p. 34).

5. Key educational decision-makers are likely to have strong intuitions and deeply held philosophical convictions about the nature of specific domains, such as, say, mathematics, and how these must be taught in light of their more general views about the nature of cognition. Such deep-seated intuitions, though implicit and invisible, can play a powerful and perhaps pivotal role when it comes to evaluating the tenability and plausibility of new teaching methods and practices. For further discussion of how certain philosophies get embedded and infused into the warp and weft of our everyday thinking through our sociocultural practices and institutions, see Hutto (2020).

6. We follow Shapiro and Stolz (2019) in supposing that the question of interest is not "whether embodied cognition might help to inform educational practices, but how" (p. 26).

7. Work on enactive metaphors is in part inspired by Lakoff and Johnson's (1980, 1999) attempt to show that abstract concepts have their roots in metaphors grounded in embodied activity.

8. A standard assumption, as Glenberg (2008) reports, is that "perceptual systems are used to encode the mathematical information, but then the cognitive processes are independent of any perceptual information such as modality of presentation" (Glenberg, 2008, p. 358).

9. The Berkeley-based Embodied Design Research Laboratory began research and design of the MIT devices in 2008, focusing on proportions (Abrahamson et al., 2016). MITs have been implemented successfully to create effective learning opportunities for young children studying challenging

concepts, including area (Shvarts, 2017), the Cartesian coordinate system (Duijzer et al., 2017), and parabolas (Shvarts & Abrahamson, 2019).

10. It would be interesting to conduct quantitative experiments to systematically evaluate what the effects, if any, embodied problem-solving using MITs might have on students' performance in more canonical symbol-based mathematical tasks.

11. Providing such an account would answer sceptics who hold that REC accounts are not capable of giving a full general account of cognition, since mathematics is typically held up as posing the greatest challenge for such approaches to cognition to accommodate (see, e.g, Núñez, 2008).

12. In rejecting the last vestiges of the information-processing framework of classical cognitivism, REC gives a quite different account of the data gleaned from neuropsychology that emphasize action-oriented processes, brain plasticity, and neural 're-use' (Anderson, 2014; Gallagher, 2017).

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II LANGUAGE

4

The Embodiment of Letter Perception: The Importance of Handwriting in Early Childhood

Karin H. James

Action has long been known to play a strong role in perceptual development. A large number of studies have shown the importance of action, and specifically self-generated action, in visual perceptual development and many different domains of cognitive development (e.g., Bertenthal & Campos, 1987; Bushnell & Boudreau, 1993; Gibson, 1969; Needham et al., 2002). In childhood, we learn to associate self-generated actions with percepts to construct representations of objects. Active interaction with the world facilitates learning about three-dimensional objects (Deloache, 1989; James & Swain, 2011; Piaget, 1953), depth perception (Richards & Rader, 1981; Wexler & van Boxtel, 2005), various types of spatial processing (Christou & Bülthoff, 1999; Held & Hein, 1963; Wohlschläger & Wohlschläger, 1998), eye-hand coordination (Needham et al., 2002), and mathematical concepts (Alibali & Nathan, 2012; Marquardt Donovan & Alibali, chapter 10 in this volume).

Visual perception also uses information gained through action—locomotion, handling objects, head movements. Thus, we perceive in order to act, and we act in order to perceive (Gibson, 1979). All these coupled experiences of perception and action sculpt connections among sensorimotor brain systems that support typical cognitive development. For this knowledge to be useful for educators, we must address how active interaction with the environment has specific effects on learning in a school setting. Of the many educational competencies that are positively affected by self-generated action, one that is often not considered is learning to read. In what follows, I will review the importance of letter recognition for learning to read, how learning letters is affected by self-generated action—specifically handwriting—and review how brain imaging can help us understand why handwriting is important for letter learning. For educators, this chapter is intended to provide information regarding how we can improve letter knowledge (and subsequent literacy) through self-generated action, and importantly *why* handwriting has these positive effects on letter learning.

Letter Recognition Is an Important Emergent Literacy Skill

Emergent literacy consists of the early skills and knowledge required for reading and writing (Sulzby, 1989) and includes phonological awareness, oral language skills, conceptual processing, and letter knowledge (Whitehurst & Lonigan, 1998). One of the earliest of these skills to emerge in the preschool years is letter knowledge—visual letter recognition and translating letter orthography to its corresponding phonology (Whitehurst & Lonigan, 1998). The ability to identify letters visually in preschool is the single highest predictor of short-term and long-term literacy success (Stevenson & Newman, 1986). Further, visual letter identification in preschool significantly influences the acquisition of phonological skills (e.g., Bowey, 1994; Stahl & Murray, 1994; Treiman & Broderick, 1998), which is a significant later predictor of literacy skill. Therefore, increasing letter identification skills in preschool may be crucial for typical literacy development.

Indeed, Denton and colleagues report that children who are proficient in identifying letters at entry into kindergarten show stronger skills at the end of kindergarten and in first grade on measures of phonological processing and word reading compared with children who are not proficient (Denton & West, 2002; West et al., 2000). The National Early Literacy Panel's (2008) meta-analysis of the research studies investigating relations between emergent literacy skills in the preschool period and reading skills at school age identified alphabetic skills as strong predictors ($r = 0.48$–0.54) of decoding, comprehension, and spelling (McGill-Franzen, 2010).

In short, letter knowledge in preschool is a significant predictor of subsequent literacy acquisition. Therefore, it is important to discover methods to facilitate early letter recognition that can be easily implemented in the classroom. One such method is increasing the time spent on printing letters by hand.

Handwriting Experience and Letter Knowledge Acquisition

Handwriting is an action requiring fine-motor skill that shares similarities with the self-generated actions that are typically studied, such that it requires a visually guided, goal-directed action of the hand. Instead of directly acting on an existing object, however, handwriting *creates* an object. It is important to note that throughout this chapter when I refer to handwriting, I am referring to any production of a symbol form by hand and utensil, with the caveat that the production creates the form, stroke by stroke, and results in a visually perceived form. This definition of handwriting, therefore, does not apply to typing or keyboarding because the output of that motor act appears all at once, and production does not involve creating the form stroke by stroke.

In addition, I distinguish between handwriting "free form" and tracing (external visual cues that aim to guide the production of the letter). Although tracing does satisfy our criteria, it also restricts the way in which the student produces the form. This distinction will be outlined more in depth later. It is also important to remember that the definition of handwriting here is not restricted to writing in cursive script: I am referring to manuscript *printed* letters, given that the age ranges of the children I am considering here have usually not been taught to write in cursive script.

Importantly, because handwriting creates letters it has a direct link to visual letter processing and has been shown to increase early letter knowledge for preschool children (for a review, see Hall et al., 2015). By some accounts, however, preschool children only spend about one minute of their school day practicing handwriting (Pelatti et al., 2014). The disconnect between educational practice and basic research findings may be due, in part, to the actual research itself—only a handful of studies have studied handwriting in isolation as an intervention in preschool (Aram & Biron, 2004; Hall et al., 2014; Longcamp et al., 2005).

It is most important when determining the effects of handwriting experience on emergent or early literacy to have control groups that allow the researcher to make valid conclusions about a given intervention. As we will see later, this is not always easy. Having children write a letter takes time, effort, high attentional demands, visuomotor skill, and visual perception of dynamic forms. Therefore, finding a control condition that is equal in all of these domains except for the single manipulation of interest is challenging. Added to this issue is the challenge that researchers face when trying to conduct experiments in a school setting versus a laboratory setting. In general, research in school settings is far less controlled than laboratory studies, so interpretations of research results from these two settings should bear this in mind. On the other hand, research in laboratory settings suffers from samples that are generally from a restricted part of the population (caregivers who have the means and time to visit a laboratory with their preschool child) and often are small. In the literature review below, I include studies both from the school setting and the laboratory setting with a specific consideration for the way in which handwriting is measured and the control groups that are used.

Although there are increases in understanding the importance of early handwriting for literacy acquisition, most studies focus on the early elementary school years, a time when handwriting becomes important for spelling, conveying ideas, and understanding the communicative nature of written language (for interested readers, see the meta-analysis by Graham, 2012; Berninger, 1994, 2012; Treiman & Broderick, 1998; Treiman & Kessler, 2014). In comparison, there are few experimental studies on the effects of handwriting in preschool on *emergent* literacy. In one such study, Hall et al. (2014) used a teacher-student sharing technique to increase the amount of text a child wrote in a group setting with an instructor. The treatment group in this study spent ten to fifteen minutes per week constructing meaningful text with an instructor over an eighteen-week period. Significant differences were found for the treatment group versus the control group for identification of both uppercase and lowercase letters. The control group, however, received no such interactive instruction, so it was difficult to discern whether the positive effects were due to the handwriting instruction or general social interactions/fine motor skill practice and/or increased exposure to print stimuli.

Another study compared shared literacy activities, *including* (but not limited to) handwriting practice with shared mathematical activities and controls, and showed that only the group who received the literacy intervention showed increased emergent literacy skills (DeBaryshe & Gorecki, 2007). This study, however, did not target handwriting specifically, so it is not known which component (or all) of the interventions had the faciliatory effect on emergent literacy.

In a review of the relevant literature, Hall et al. (2014) found only eighteen studies that explicitly tested the effects of handwriting in preschool on emergent literacy. Of these eighteen studies, only five used letter formation by hand as an intervention (Aram, 2006; Aram & Biron, 2004; Longcamp et al., 2005; Lonigan et al., 2011; Neumann et al., 2013). In the study by Neumann et al. (2013) children were asked to write a letter in the sky and in a personal journal after teacher demonstration. The intervention was for eight weeks, at thirty minutes twice a week in small group settings. In the Lonigan et al. (2011) study, children were encouraged to write the letters in their names in a similar intervention schedule. In both studies, the children in the experimental group showed increased expressive knowledge, phonological awareness, and print knowledge compared with the control groups. These interventions, however, (1) only used the letters in a child's name, and (2) did not compare various intervention types (similar to the Hall et al. study mentioned previously); therefore, the results may have been due to any intervention at all compared with a control.

Two studies by Aram and colleagues involved a twice weekly intervention in a small group setting that involved three intervention groups: (1) joint writing with stickers (instead of with a utensil), (2) joint reading, and (3) a control group (Aram, 2006; Aram & Biron, 2004). This research revealed that the "writing" group progressed more than the other groups in letter knowledge and letter-retrieval measures. One shortcoming of this intervention was that only the writing group had sensorimotor interactions with letters compared with the reading-alone group, the control group, and to a lesser extent the reading and "writing" group. Further, these students did not do actual handwriting; rather they performed a sensorimotor skill that involved manual dexterity with a sticker that produced, in a self-generated manner, the letterforms.

Comparing actual handwriting with other sensorimotor interventions is an important factor in demonstrating the possible efficacy of handwriting itself on letter recognition. This type of intervention was addressed in a study by Longcamp and colleagues (2005). In this study one group of children learned to print letters while another group typed the letters. They provided the intervention in a laboratory setting once per week for twenty minutes for eight weeks. Letter recognition was enhanced only for the printing intervention group but also only in older children, aged 4.5 years. This was the first study at the time to control for visuomotor experience and time on task, as both groups used their motor systems to produce letters, saw the resultant letters (although the perceptual differences between the two types of productions are of note), and spent relatively equal amounts of time during letter production. Although the gains from the practice were not assessed past one week of the intervention, this study still remains as one of the most conclusive behavioral results demonstrating a clear benefit of handwriting training.

A recent study controlled for visuomotor production effects by comparing writing letters with writing digits and their effects on subsequent letter knowledge tasks (Zemlock et al., 2018). In this study, preschool children were tested on their change in letter knowledge (naming, categorization, and recognition) before and after an intervention within the school setting. The groups included (1) letter writing practice, (2) letter naming practice (visual only), (3) digit writing, and (4) digit naming. Here the researchers were not only interested in differences between handwriting and naming but also in discerning whether the handwriting experience had to be specific to letterforms. There was a clear and significant benefit to writing letters and digits compared with the naming-only conditions. In addition, although writing letters resulted in greater gains than writing digits, these gains did not reach statistical significance—both writing letters and writing digits facilitated letter knowledge skills. Therefore, it appears that practice in creating a form by hand may be a more general mechanism by which letter knowledge can be increased.

To try to determine what it is about handwriting that has positive effects on letter knowledge, I and my colleague ran a study that compared various methods of learning a novel symbol set (Greek letters) (Li & James, 2016). In this research, children learned Greek symbols in one of five conditions that varied along two broad dimensions: (1) whether during training the child produced the form by hand (either through copying or tracing) versus viewing the form and saying the name of the form, and (2) how the training forms were manipulated. The hypothesis from this group was that handwriting benefits symbol learning because it produces variable forms.

It is well known that when learning a category, children benefit from seeing variable exemplars from that category (e.g., Perry et al., 2010). Handwritten letters produced by young children are highly variable but always are called by the same name. Thus, the category of the letter (formed by its name) is defined by a high amount of variability that broadens the category boundaries, allowing for increased letter recognition. In our study (2016), we compared symbol categorization ability after children learned symbols through either copying the symbols by hand free-form (handwriting produced and variable), tracing handwritten examples of the symbols (produced and variable), tracing multiple typeset fonts (produced and variable), visual viewing of multiple typeset fonts (not produced and variable), tracing a single font (produced and not variable), and visual viewing of a single font (not produced and not variable). The results showed that in all cases in which children learned variable exemplars of the category, recognition was enhanced (see figure 4.1).

Therefore, this research suggests that it may not be the visually guided production per se that enhances learning but rather that production usually results in variable forms and this variability facilitates category learning. The results of this study indicate that handwriting is important for letter learning, but if handwriting is not possible then children may benefit additionally from being exposed to text that contains multiple fonts or handwritten text.

Furthermore, the results from our study have suggested an interesting possibility: perhaps messy handwriting in the early years can facilitate letter learning. Although the accuracy of children's letter production is rarely studied, one study found that high production accuracy did correlate with letter knowledge in preschool but not in kindergarten (Molfese et al., 2011). We are also measuring whether accuracy of handwriting in preschool correlates with letter recognition measures (James, unpublished).

In sum, there are few studies to date that have experimentally investigated the effects of early handwriting instruction on emergent literacy skills. We know, however, that in many circumstances handwriting practice does appear to have a positive effect on emergent and early literacy skill. Before considering the question of *why* handwriting has this effect on letter learning, it is important to consider the complexity of the act of handwriting itself.

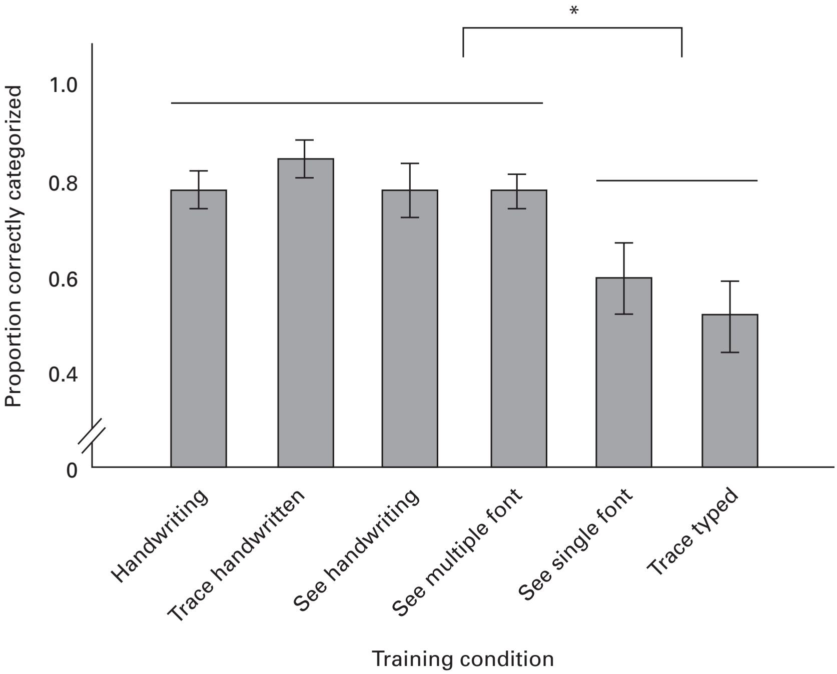

Figure 4.1
Results from Li and James (2016) showing that all conditions during which children were exposed to variability in exemplars resulted in greater categorization ability compared with conditions with less variability. Reprinted with permission.

The Complexity of the Handwriting Process

The interrelated behaviors involved with handwriting include fine-motor guidance of the fingers, hands, and wrists as they control a writing utensil (also eye-movements, postural control, head movements, arm movements) (Feder & Majnemer, 2007; Trieman & Kessler, 2014). In children, the manipulation of the writing utensil is difficult, given their immature fine motor skills. This immaturity results in variations of the standard sequence of hand movements for each letter that they attempt to write. Even in the most proficient adult writers, each time a letterform is produced, the motor behavior changes as a function desk height, pen weight, paper roughness, lighting, torso positioning, and muscle fatigue.

Although the *general* movements required to produce a given letterform may be fairly standard across productions, the actual force, velocity, and trajectory of each movement is highly variable from one production to the next

(Wing & Nimmo-Smith, 1987). If we consider the real-time act of handwriting, given that the production of a legible letterform varies from one episode to the next, we can assume that there are unique perceptuomotor interactions involved with each episode (Feder & Majnemer, 2007). It is important to note that although letter production requires access to motor plans (Gallivan et. al., 2013; James & Gauthier, 2006; Longcamp et al., 2003, 2014), these plans only serve as a rough guideline for the production of the shape: The in-the-moment production, on the other hand, requires the efficient interplay of environment, perception, and action.

The output of the motor production is the form on the writing surface that is then visually perceived and guides subsequent movements. This perceptual experience involves seeing the dynamic unfolding of a letterform stroke by stroke, one's hand and pencil moving in time with the unfolding letter, and the observation of the final handwritten letter. These perceptual experiences serve not only to guide the ongoing motor behaviors in real time but also may be stored to influence subsequent letter perception and/or production—potentially to augment motor plans in real-time based on visual feedback. Importantly, the resultant percept is highly variable in its final form and in the dynamics during production. With a very immature motor system, for instance, this perceptual variability in the resultant form from one production to the next can be quite significant (see figure 4.2 for an example). This perception-action loop culminates in the production of meaningful visual stimuli that are the seemingly simple result of a very complex set of behaviors.

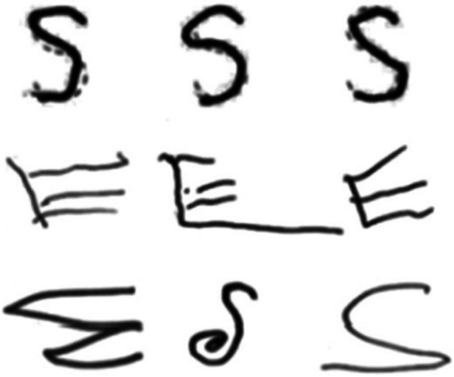

Figure 4.2
The top two rows are productions by the same four-year-old child. The bottom row contains productions by different children. Reproduced from Li and James (2016).

Mechanistic Approaches to the Relationship between Handwriting and Letter Knowledge

There is consistent evidence that handwriting practice in young children facilitates symbol understanding. The mechanisms that support this relationship likely involve an interaction among motor systems involved in self-guided action and perceptual systems that support visual recognition.

One idea is that during visual perception of letters, the motor system which was engaged during past production events is reactivated and affects the visual system during recognition. Because experience with letters has been embodied, the system that supports any experience with letters therefore would involve both sensory and motor subsystems. In essence, what we would usually think of as a perceptual task (letter recognition) activates a broad system of sensorimotor brain regions. A series of elegant studies by Freyd and colleagues showed that when we perceive a static letter, we use our motoric experience to affect recognition—that we perceive cues in the letterform that reflect how it was produced (Babcock & Freyd, 1988; Freyd, 1983a, 1983b; Freyd & Finke, 1984, 1985). This work suggests that writing a letter and visually perceiving a letter may share underlying mechanisms.

One way to further investigate this idea behaviorally is through the use of a dual task paradigm. In such experiments, two behaviors are required at the same time (perhaps talking and walking). If those two behaviors share neural systems, then performing them at the same time will come at a cost—measured by increased reaction times or decreased accuracies—relative to performing two tasks that do not share mechanisms. One such study showed that writing letters and perceiving letters interfered with one another, leading to decreased performance in both tasks relative to when they are performed in isolation or with noncompeting behaviors (James & Gauthier, 2009). In this study, adult participants were required to continuously write a single letter or draw a single shape on a touch pad (without looking) while naming letters and shapes masked in Gaussian noise on a computer screen (see figure 4.3). The results showed that when writing letters, but not while drawing shapes, their letter identification was impeded. Shape identification, however, was not affected by writing letters or drawing shapes. These results suggest that letter perception and letter production share neural substrates, and that this is not due to interference from any motor behavior performed concurrently with letter perception because the effect was not observed when drawing shapes (James & Gauthier, 2009).

To more conclusively demonstrate that these two behaviors share neural mechanisms, however, one must turn to methods that measure neural activation

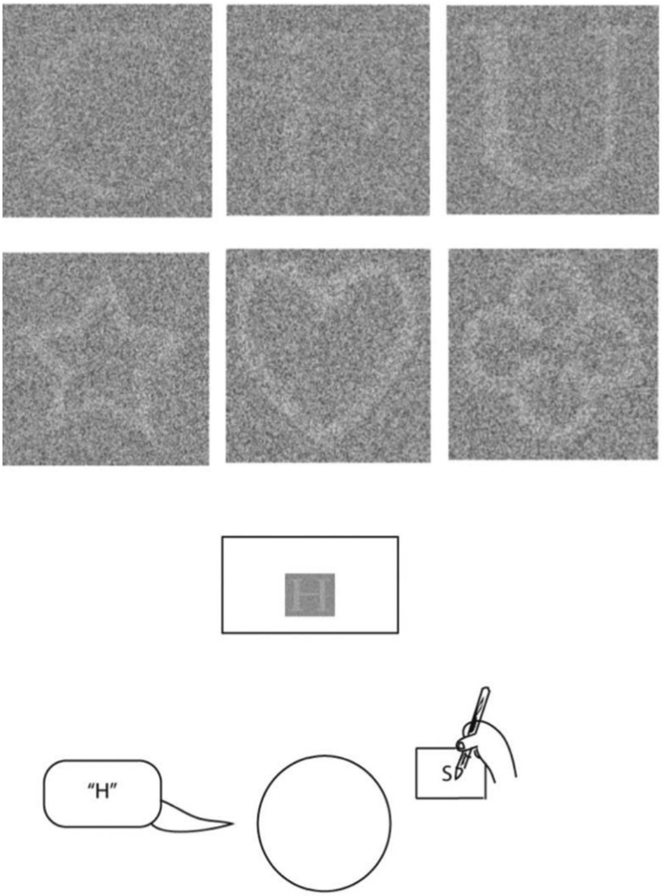

Figure 4.3
Stimuli and procedure used in the dual task paradigm in James and Gauthier (2009). The top two rows are examples of stimuli imbedded in Gaussian noise masks (to make perception more difficult). The schematic below shows participants writing a letter while identifying a letter or shape on a computer monitor.

during behaviors. One such measure that has been used for this purpose is functional magnetic resonance imaging (fMRI).

Why Handwriting Affects Letter Recognition: Neuroimaging

Functional MRI is, by now, a well-known method that allows researchers to examine neural responses that occur during a task. In short, fMRI measures levels of the blood oxygen level dependent (BOLD) response in neural populations. The BOLD response has been found to be an accurate reflection of neural activation (e.g., Logothetis et al., 2001) as it reflects oxygen uptake in neurons as they respond to increased use. One can devise experiments very similar to those in a behavioral laboratory setting, but instead of measuring learning outcomes, one can measure neural responses via BOLD responses that occur in real time while a participant learns. The results can reveal systems involved in the learning episodes, as well as how those systems are functionally connected in the brain to support various learning outcomes.

Functional MRI is an ideal method for measuring neural changes during and after learning because it is noninvasive and can be repeated many times without any ill effects to the participants. The downside for using fMRI for studying learning in children is that the participants must keep their heads extremely still for the duration of scanning (usually five to seven minutes at a time), which makes scanning very young children virtually impossible. There are, however, studies that have measured brain changes in children from four to six years of age—the ideal time to study brain development as it pertains to emergent and early literacy.

Functional MRI can add valuable information to what we know about the importance of embodiment during learning. The simple logic is as follows: if during a purely perceptual event (seeing or hearing a stimulus for instance) motor systems become active, then we assume that the perceptual event activates the motor system because the two have become linked through prior experience. This is referred to as motor reactivation (e.g., Nyberg et al., 2001) or common coding (e.g., Schütz-Bosbach & Prinz, 2007). Not all sensory events involve motor reactivation, which has led researchers to the conclusion that if motor reactivation occurs, then the motor system must add potentially important information to the perceptual event. Given this understanding, we can then measure brain activity during various tasks to probe under what conditions motor experience affects learning.

In the case of the relationship between letter learning and handwriting, it is important to first understand the perceptual systems involved in letter perception and the motor systems involved in handwriting prior to investigating neural overlap and coactivation of systems. In terms of the perceptual systems involved in single-letter processing (as opposed to letters in words), years of research from many different laboratories have shown that the literate (adult) brain has a specialized region that is most involved with letter processing (e.g., James & Atwood, 2009; Rothlein & Rapp, 2014; Flowers et al., 2004; James et al., 2005; Longcamp et al., 2003; Polk & Farah, 1998). This region, the fusiform gyrus, is located in the ventral temporal cortex (usually responding more in the left than right hemisphere), very close in spatial terms to early visual processing regions as well as systems used for memory.

This is not to say that this is the only region involved with letter perception. There is a widespread system that is active when an individual views letters, which includes the ventral temporal cortex, the posterior parietal cortex, and several regions in the frontal cortex (e.g., James & Gauthier, 2006). Interestingly, the finding that visually perceiving letters activates frontal systems involved in motor behavior was an initial hint that letter perception was affected by motor experience.

Brain Responses during Handwriting

Letter production is a complex task that involves its own set of perceptual and motor components. The perceptual components include, for instance, visual perception, kinesthesia, and proprioception. The motor components include fine motor control, in-hand manipulation, and eye movements (Feder & Majnemer, 2007; James & Gauthier, 2006). As a visually guided action, letter production also requires efficient integration among perceptual and motor systems. Indeed, tests of visual-motor integration skill repeatedly correlate with the quality of handwritten forms (Cornhill & Case-Smith, 1996; Klein et. al., 2011; Maeland, 1992; Tseng & Murray, 1994; Weil & Amundson, 1994).

In addition, studies that have investigated the neural systems supporting handwriting have repeatedly shown that the brain regions associated with motor movements (frontal cortex), perceptual processing (ventral-temporal cortex), and perceptuomotor coordination (parietal cortex) are recruited (James & Gauthier, 2006; Longcamp et al., 2014; Yuan & Brown, 2014; for a meta-analysis, see Planton et al., 2013). We proposed, therefore, that letter production has at least three major components: motor, perceptual, and perceptuomotor coordination, and that the frontal, ventral-temporal, and parietal cortexes are differentially involved in each component (see figure 4.4).

The unique constraints of the fMRI environment, as previously mentioned—that participants cannot move their heads during scanning—limits the study of motor behavior. Interestingly, however, carefully devised experimental apparatuses can allow a researcher to measure brain activation while the participants move their hands and arms. This is especially advantageous for the study of handwriting. Writing by hand is a visually guided action defined by watching one's own hand create a form that is visually perceived as it unfolds over time. Most studies to date that have claimed to image the neural substrates of handwriting did not test it as a truly visually guided action because the participants either could not see themselves write (James & Gauthier, 2006) or could only watch their production in a mirror (without seeing their own hand) instead of directly (e.g., Longcamp et al., 2014; Tam et al., 2011). These

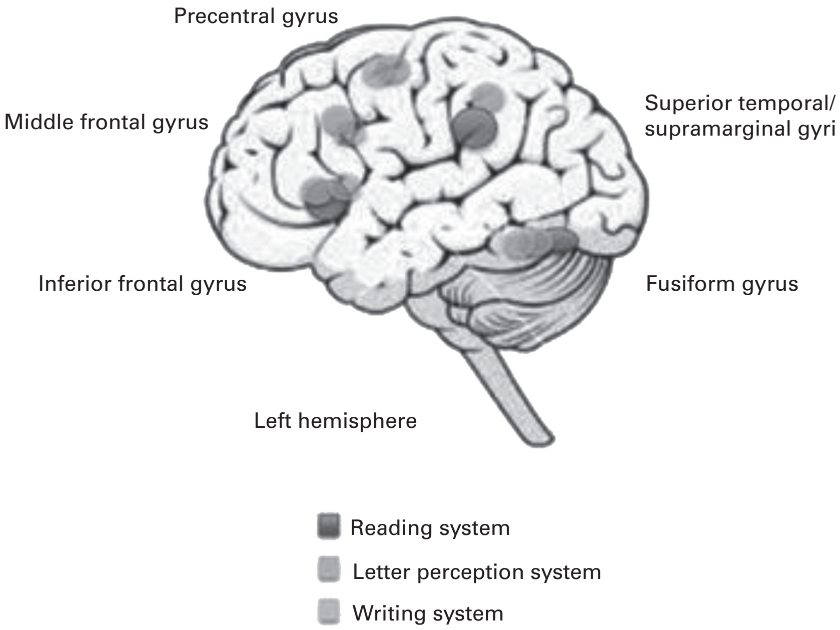
Precentral gyrus
Middle frontal gyrus
Superior temporal/ supramarginal gyri
Inferior frontal gyrus
Fusiform gyrus
Left hemisphere
■ Reading system
■ Letter perception system
■ Writing system

Figure 4.4
Schematic representation of the visual-motor letter processing systems. It is striking that given many different tasks and multiple studies, there is still substantial overlap in regions that comprise the system. Reproduced from James (2010).

limitations are based on the lack of apparatuses that are compatible with the magnetic environment. Of course, although these techniques are not ideal, they have produced useful data (for a meta-analysis, see Purcell et al., 2011).

For instance, one study compared visual perception, visual imagery, and handwriting directly in the same study comparing letters to shapes (James & Gauthier, 2006). In this study, the participants either saw a letter or a shape and either viewed it alone, imagined the appearance of the target, or wrote/drew the letter/shape. We found a highly distributed network of activity to these manipulations, with substantial overlap in some regions among the conditions. Of interest was that the frontal motor regions responded not only during writing letters but also during perception of letters (see figure 4.4); the fusiform gyrus, in the visual association cortex, responded to visual perception and also during handwriting.

As stated, however, handwriting is a complex behavior. It is therefore not surprising that letter production recruits a widespread system of brain activation. It turns out that each of the regions in this system have a specific role to play during letter production. By separating the components of handwriting

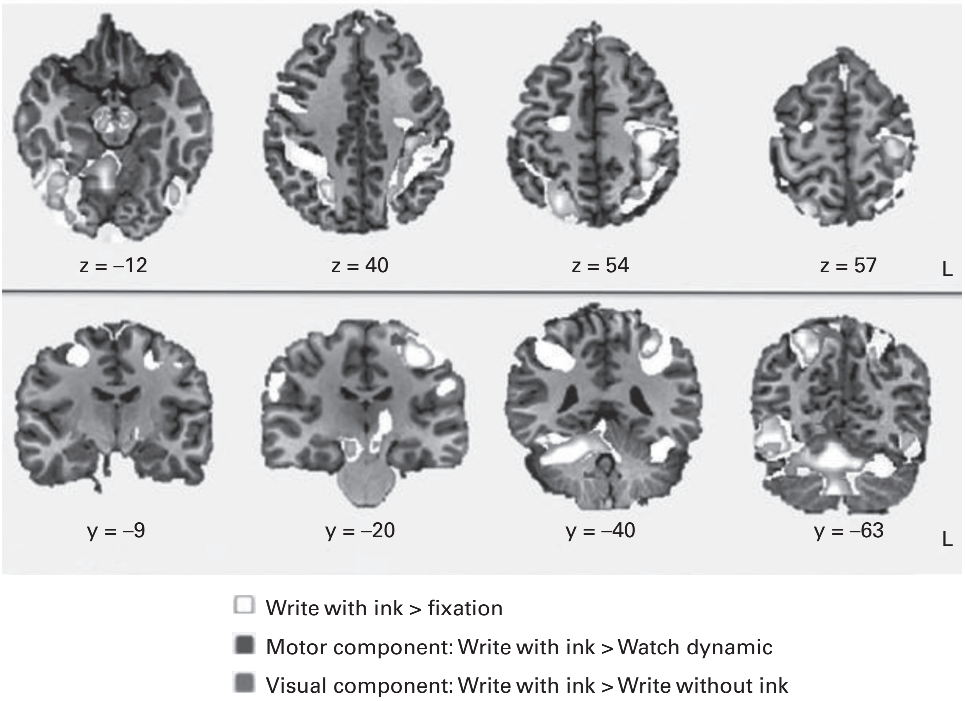
z = −12
z = 40
z = 54
z = 57
L
y = −9
y = −20
y = −40
y = −63
L
☐ Write with ink > fixation
■ Motor component: Write with ink > Watch dynamic
▨ Visual component: Write with ink > Write without ink

Figure 4.5
Separating handwriting into motor and visual components shows regions that are involved in motor and visual processing only, but also areas that are visual-motor, as depicted by overlap. Reproduced from Vinci-Booher, Cheng, and James (2019).

into motor, perceptual, and perceptual motor, one study found that the motor component of handwriting was supported by the left dorsal frontal, left posterior parietal cortex, and the right ventral temporal cortex (Vinci-Booher et al., 2019). The visual component recruited the posterior parietal and ventral temporal cortices bilaterally, and the perceptual-motor component recruited the bilateral ventral temporal cortex and the left posterior parietal cortex (figure 4.5). Thus, the same triad of regions were recruited as was seen in other studies on handwriting, but the purpose of each was now elucidated.

The Development of the Letter Processing System

The work mentioned so far was performed on literate adults who could also write. But how does this brain system involved in letter processing develop? That is, does handwriting experience lead to this widespread processing that is observed during letter perception? Although the research on young children and the development of letter processing has been limited, it is conclusive (see James, 2017, for summary). Handwriting practice leads to the specialized brain response that we see in literate adults when they perceive letters.

The first study to show this relationship used fMRI and a training paradigm to investigate the question of whether handwriting experience led to changes in the brain's response to viewing letters (James, 2010). Four- to five-year-old participants were scanned before and after training, and the training involved either practice printing a set of letters, shapes, and pseudo-letters or practice with the "see and say" method of learning the three types of stimuli. The results showed that only the children who had practiced letters through handwriting showed adult-like activation—an increased BOLD response to letters relative to other stimulus types—when subsequently viewing letters (see figure 4.6).

A follow up study included additional groups who learned letters through tracing and typing (in addition to the printing group) (James & Engelhardt, 2012). Again, only handwriting practice resulted in the typical brain response to letters seen in literate individuals. That is, there was more activation in frontal and ventral temporal regions after printing practice than typing practice. Also, there was greater activation in parietal cortex after practice printing compared with practice tracing, and increased activation in a medial frontal region after tracing compared with typing. These results suggested that handwriting practice increased activation during letter viewing in the letter processing system not only more than typing but also more than practice tracing. This latter result was interesting because it showed that tracing, also a fine motor skill, did not recruit the same system. If we interpret this result along with the results from Li & James (2016), outlined earlier, tracing a typed letter would not involve seeing variable forms. Thus, the results from this neuroimaging study suggest that producing variable handwriting forms is an important component in the activation of the distributed letter system.

Furthermore, the frontal motor areas that were active in this study become functionally connected (the coactivation that occurs in regions is due to the task itself) to the ventral temporal visual regions of the brain *only* through handwriting practice in young children, not when children practice typing letters (Vinci-Booher et al., 2016).

Recently, a direct comparison was made among young children's, older literate children's, and adults' production of letters in terms of brain systems that supported letter perception (Vinci-Booher & James, 2020). That is, when we produce a letter by hand, we see both the dynamic unfolding of the letter stroke by stroke and the complete letterform that we have produced. In addition, handwritten letters look different from one production to the next (they are

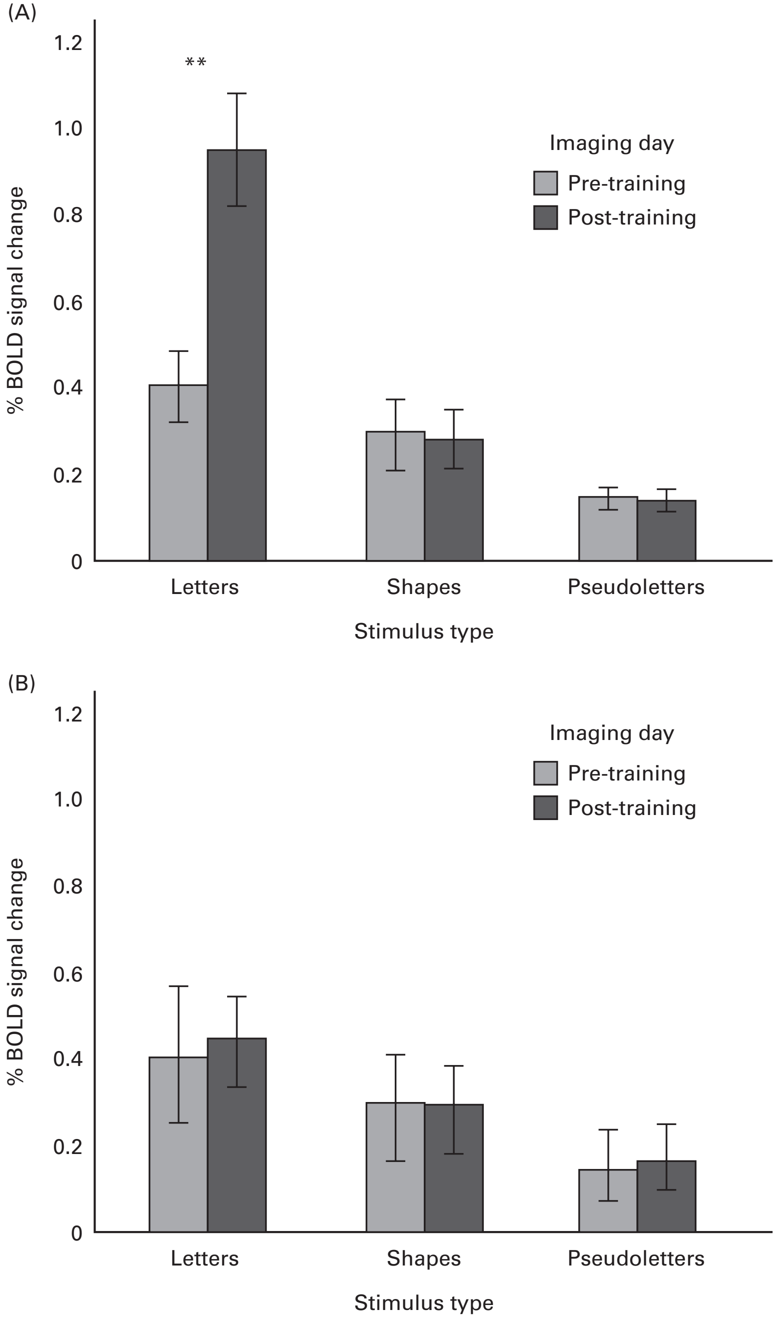

Figure 4.6
BOLD data extracted from the left posterior fusiform gyrus. (A) The group of children who practiced writing letters showed a significant increase in response after training. (B) The children who practiced letters in a "see and say" method did not. Reproduced from James (2010).

variable) and are easily identified as being handwritten. There is even evidence that we can easily recognize our own handwritten letters (Knoblich & Prinz, 2001; Knoblich et al., 2002). Our study (Vinci-Booher & James, 2020) was the first to measure production and perception in a scanner in which the participants directly saw their own hand and productions rather than looking in a mirror (see figure 4.7). This was accomplished by the use of a magnetic compatible tablet (MRItab) (Vinci-Booher et al., 2018), which allowed the participants to write directly on it while seeing their own productions and also allowed for the playback of the participants' productions within the same experiment without moving the participant.

The results from this study gave the field some interesting findings. First, as was seen in previous work with four- and five-year-old children, the brain did not respond to typed letters more than regular shapes. That is, there was no neural specialization for letters at this young age (presumably because they did not have enough experience writing letters—as the previous research had demonstrated). The youngest children, however, did show a neural response in the fusiform gyri to *handwritten* letters. Therefore, their brains did show specialized letter responding, but only when they were shown these variable, messy, examples of letters (see figure 4.2). The older children and adults showed activation to the typed letters, and no difference in response for the handwritten letters compared with the typed letters. Thus, once reading and writing have been established, the brain systems respond to any type of letterform in the same way. We draw two main conclusions from this study: (1) adult-like letter processing occurs earlier in the ventral-temporal cortex

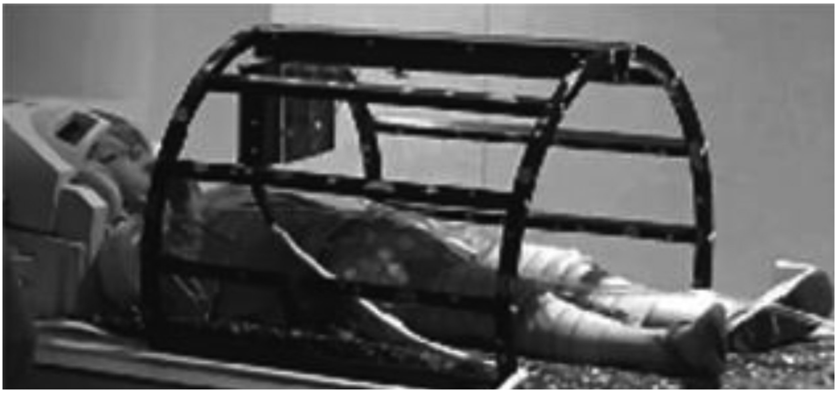

Figure 4.7
A depiction of the MRItab and associated apparatuses that can track handwriting and perception within the same unit, allowing for ecologically valid measures of handwriting production and perception. Reproduced from Vinci-Booher and James (2020).

than in the parietal and frontal motor regions, and (2) the perception of variability in letterforms that occurs during letter production may lead to this development (Vinci-Booher & James, 2020).

The neuroimaging data to date have demonstrated that handwriting experience serves to activate both visual and motor regions of the brain and connects them into a system that then responds whenever a letter is encountered. Because we have embodied experience with letters through handwriting, perception is not only visual but also involves an integrated system that reflects our motor experiences. Interestingly, neural responses to handwriting events (perceptual, motor, and perceptuomotor) change through development as the integrated system develops.

Conclusions

Handwriting experience in preschool and early elementary school facilitates letter recognition—an important emergent literacy skill. This embodied experience affects visual letter perception by creating a system that links visual with motor brain systems. When first learning to write, the immature motor system provides visual input that is highly variable, which serves to create accurate categorization of exemplars. Once one is proficient at writing and reading, the visuomotor system is well established and activated during letter perception and letter writing.

For the educator, the message is quite simple. Printing practice in preschool and even in the early elementary years is important for letter learning. The experience, however, is specific to free-form handwriting, not to tracing letters or keyboarding. Accuracy in producing the letterform does not seem to be important, so young children should be encouraged to produce letters frequently, without correction in accuracy.

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5

Embodied Classroom Activities for Vocabulary Acquisition

Ligia E. Gómez and Arthur M. Glenberg

An essential component of literacy—in both the native language and additional languages—is vocabulary. For example, multiple studies have focused on the influence of vocabulary knowledge on reading outcomes in English and in a variety of other languages (e.g., Lesaux et al., 2007; Snow et al., 1998). In addition, there is a literature on the role of rich vocabulary knowledge and its relation to comprehension (e.g., Proctor et al., 2012). Other studies have focused on the role parents and the social environment have on language development (e.g., Huttenlocher et al., 2010; Hoff, 2006). But how is that vocabulary learned in a formal setting such as a classroom or even in the home? The answer from standard accounts of cognition is usually a variant of repetition of the vocabulary list: read the word, read its definition; read the word, read its definition; read . . . Can we do better by approaching vocabulary acquisition from the perspective of embodied cognition?

We begin this chapter with a brief overview of an embodied theory of language comprehension (for a fuller account, see Kaschak & McGraw, chapter 6 in this volume, or Glenberg & Gallese, 2012). Based on this theory, we offer a few suggestions for how a classroom teacher can enhance vocabulary learning. Finally, the bulk of the chapter comprises a review of several research projects implementing some of these suggestions.

Embodied Language Comprehension

How do we understand a sentence such as "While walking in the Grand Canyon, the hiker was awestruck by the towering red rocks?" Traditional views of language comprehension would detail processes such as lexical access and syntactic organization. An embodied account emphasizes a different type of account: we use the words and phrases in the sentence to drive sensorimotor and emotional systems into states that are homologous to those experienced by actually being in the situation described by the sentence. The notion of driving the system is also called simulation, grounding, or, more prosaically, imagination (although there is no theoretical requirement for that imagination to be conscious). How does this abstract statement apply to our sentence about the hiker in the Grand Canyon? The phrase "while walking" is used to drive the cortical motor system into a state that is similar to actually walking; the phrase "towering red rocks" is used to drive the cortical perceptual system into a state that is similar to literally seeing towering red rocks; and to understand "awestruck," we call on the emotional system to produce a state similar to that of being awed. It is this process of simulation that gives immediacy to language and makes it feel like we are participating in events, not just reading words.

There is a growing amount of research, both behavioral and neurophysiological, that supports this approach to language comprehension. For example, Hauk et al. (2004) provide one of the most compelling demonstrations of motor system involvement in language. Their participants listened to action verbs such as "lick," "pick," and "kick" while their brains were being scanned with functional magnetic resonance imaging (fMRI) (i.e., tracking the flow of oxygenated blood to particular areas of the brain). Upon hearing the verb "lick," increased blood flow appeared in the motor system, and that activity was most evident in just that portion of the motor system used in controlling mouth movements. Similarly, on hearing "pick" and "kick," the activity was most evident in areas used in controlling the hand and leg, respectively. That is, on hearing the words, the participants were simulating or grounding the meaning by activating the motor cortex in ways similar to literally licking, picking, and kicking.

There is also a tremendous amount of work demonstrating simulation using perceptual systems. For example, Rueschemeyer et al. (2010) used fMRI procedures to examine activity in V5/MT (the fifth visual area located in the brain's middle temporal lobe) while individuals read sentences. This area of the brain had previously been identified as important for the processing of visible motion. Would it also be active when processing sentences *describing* visible motion? The researchers presented sentences that described motion toward ("The car drives toward you"), motion away ("The car drives away from you"), or no motion ("The car looks big"). They found more activity in V5/MT while understanding the motion sentences than when understanding the no motion sentence (although the results were not statistically significant for the "away" sentences). That is, people were using the visual system to simulate or ground the described motion in the motion sentences.

Comprehension of sentences with emotional content has been tied to the emotional system (Havas et al., 2010; Havas et al., 2007). For example, Havas et al. (2007) found that when people were smiling, they were faster to understand sentences describing pleasant situations than when they were frowning. Apparently, priming the emotional system by having people smile helps them to simulate and understand sentences with congruent content.

Application to Vocabulary Acquisition

The embodied theory of language comprehension has strong implications for vocabulary acquisition. Namely, if words are used to create embodied simulations, then when learning the meaning of a word it is necessary to connect the symbol (i.e., a word's spelling or pronunciation) to sensorimotor and emotional content. Otherwise, the word is an empty shell.

This linking or grounding (or *indexing,* to use the terminology of Glenberg & Robertson, 2000) is often acquired in naturalistic contexts. For example, a mother might say, "Here is your bottle," while simultaneously handing the infant the bottle. Thus, the infant learns the link between the symbol "bottle" and its sight, feel, knowledge of how to act on the bottle, and the pleasant emotions associated with drinking, such as quenching thirst and being held by the caregiver.

At other times, the link between symbol and meaning can be inferred from context. Consider learning the novel word "kapotsek" in the following context: "The farmer was frustrated because every evening his cows would push open the barn doors and scatter around the pasture. To overcome this problem, he attached a rope loop to each door, and then he passed a kapotsek through the loops. That way, the cows couldn't push open the doors." From this scenario, you can describe many features of a kapotsek that were never mentioned: its probable length, the type of material it is made of, its thickness, and so on. How can you do this? By creating a sensorimotor simulation based on "barn door," "loop," and "pass through," you constrain the possible meaning of kapotsek. That is, learning the meaning of the word kapotsek did not require a verbal definition. Instead, it required the creation of a sensorimotor grounding.

As an adult who is a skilled reader—that is, someone who is fluent at creating simulations—you do not need any help in generating a simulation that helps in learning the meaning of words like kapotsek. By contrast, a child faced with a list of vocabulary words, each with its own definition (rather than a narrative about cows), may need some help to form the simulations. This is particularly true if the words in the definitions are also unfamiliar and thus require construction of their own simulations.

Four Embodied Classroom Activities for Vocabulary Acquisition

We organize these four activities by the target age of the students: preschool, primary school, students learning a second language, and college students learning an abstract mathematical concept. The activities we describe are by no means meant to be an exhaustive listing of the possibilities. Instead, they are intended to be illustrative of how a teacher can incorporate principles of embodiment into teaching with a focus on vocabulary.

Supercharging Dialogic Reading with Preschool Children

An important source of vocabulary for young, preliterate children is shared reading (i.e., having a parent or teacher read a book with the child). Shared reading often introduces vocabulary that is outside of daily routines, thus providing the opportunity for building vocabulary. A systematic method of shared reading is called dialogic reading (e.g., Zevenbergen et al., 2018). With dialogic reading, the adult asks questions related to the text that are intended to prompt dialogue. The dialog promotes text understanding and vocabulary acquisition.

Most examples of dialogic reading are purely verbal. For example, Zevenbergen et al. (2018) provide this example of the PEER—prompt, evaluate, expand, and repeat—strategy: “Adults are taught to provide a *P*rompt to the child (e.g., ‘What is this?’), *E*valuate the child’s answer (e.g., ‘You are right! It is a sheep’), *E*xpand on the child’s utterance (e.g., ‘The sheep has a wooly coat’) and ask the child to *R*epeat the longer utterance (e.g., ‘Now you say it: The sheep has a wooly coat’)” (pp. 862–863). This process is designed to teach vocabulary such as “sheep” and “wooly” as well as having the child practice longer utterances and syntax. If the child does not already know what wool is, however, this sort of process might not do a good job of teaching the concept.

An embodied approach to this situation might include manipulatives such as a skein of wool or a wool sweater. Then, the parent could have the child feel the wool, map the sight of the real wool to the picture, and ask the child to put on the sweater and relate it to the sheep’s wooly coat. Indeed, a study by Wall et al. (2021) investigated whether procedures that ground meaning in sensorimotor activities like these really help children to learn vocabulary. They created triplet groups composed of preschool children (average age of four years, nine months) who were matched on age and Peabody Picture Vocabulary Test scores. One child in each triplet was randomly assigned to each of three conditions. In the control condition, a child and an experimenter listened to a commercially available electronic story presented on an iPad and accompanied by pictures. They listened to the story once a day for eight days. The children took tests at three time points: before any listening (pretest), after the fourth listening (midtest), and after the eighth listening (posttest). There were two types of tests: the comprehension test asked questions such as “What animal does Ahmad take on his trip?”; the other test was of twenty vocabulary words (e.g., the child was asked “What do you think ‘startle’ means?”).

The second condition was called “dialogic-then-combined.” As in the control condition, the children heard the story eight times and took the pre-, mid-, and post-tests. For the first four times of listening to the story, the experimenter followed a script that implemented dialogic question asking. The dialogic questions targeted twelve of the twenty tested vocabulary words. For example, on the first listening, the script targeted the word “startle”: “Why does Ahmad wake up? That’s right! He was startled. That means to feel frightened or scared. Can you say startled?” Then, on the third reading the script read, “Ahmad felt startled when he woke up. Do you remember what startled means? That’s right [or ‘Startled means feeling frightened or scared’]. Can you tell me about a time that you felt startled?”

After the fourth reading and the midtest, children in the dialogic-then-combined condition began to receive instruction based on principles of embodied cognition. These principles were implemented using manipulatives including a small doll named Ahmad, a bed, and other items. Upon getting to the word “startle,” the script read, “Why does Ahmad wake up? He was startled. That means felt frightened or scared. Because he’s startled, he jumps out of bed. Make him jump. Let’s make him startled. [The experimenter shakes the Ahmad doll and hands it to the child to shake.] Can you say startled?” Thus, the child generates sensorimotor and emotional activity to associate with the word “startle.”

In the “combined-then-dialogic” condition, for the first four listenings of the story the combined (i.e., dialogic and embodied) script was implemented; for the final four listenings, the dialogic script was implemented.

The children in all the groups showed substantial improvement from pretest to midtest, but the children who received the combined script improved the most (see figure 5.1). The statistical interaction between condition and pretest to midtest was significant with a large effect size (partial eta squared = 0.28). That is, adding the embodied activities appeared to supercharge dialogic reading.

Overall, the children did not learn many of the words (or at least, did not learn them well enough to define them on the test). Nonetheless, once again there was a large (partial eta squared = 0.30) interaction indicating that children in the combined condition showed much greater improvement from the pretest to the midtest than the children in the dialogic condition (see figure 5.2).

The children’s vocabulary did not improve for the nontargeted words. This null finding is important because it demonstrates that the improvements in the combined condition shown in figure 5.2 did not result simply from children

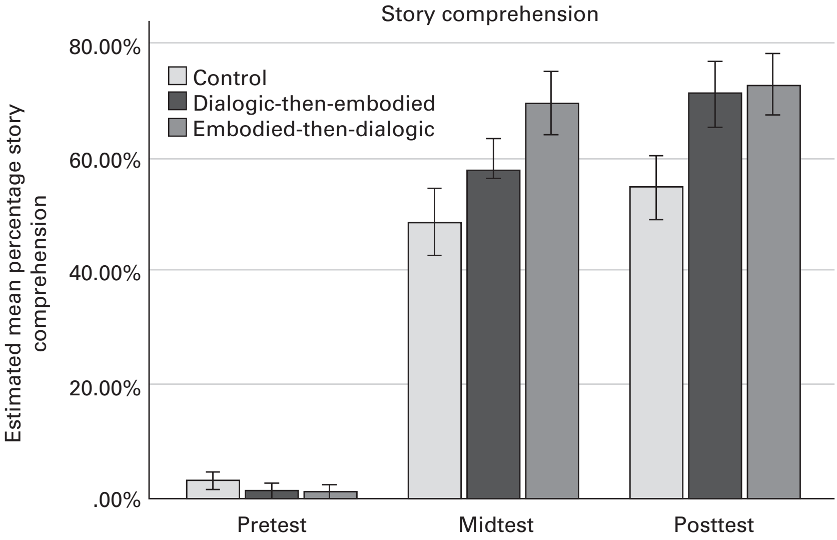


Figure 5.1
Data from the story comprehension test. Source: Wall et al. (2021).

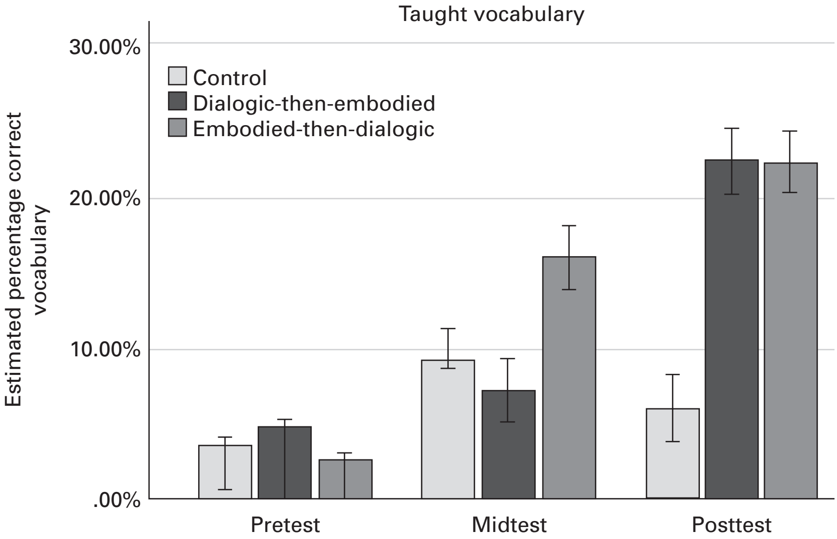


Figure 5.2
Data on acquisition of targeted vocabulary words. Source: Wall et al. (2021).

enjoying the activities more or paying greater attention to everything. Instead, the doubling of vocabulary learning (compared with dialogic reading alone) resulted from the embodied activities used to ground the target words.

Learning Physics Vocabulary in the Second and Third Grades

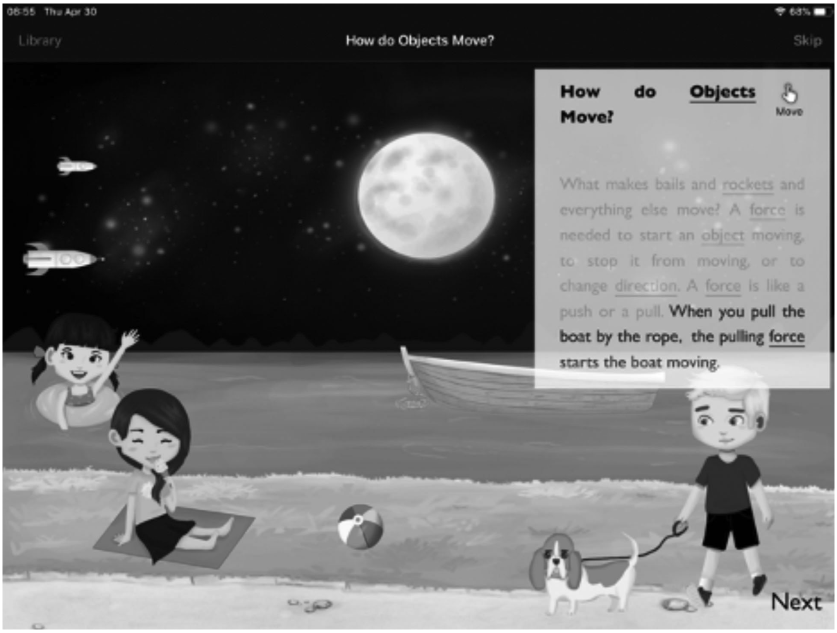
Children in primary grades are introduced, some for the first time, to higher-level vocabulary such as words presented in informational texts. Teachers use a variety of strategies to teach vocabulary, and some strategies are more efficient than others, especially during read-aloud interactions (e.g., Gómez et al., 2017). Two common strategies are for teachers to organize their classrooms into (1) thematic centers or (2) small groups. We envisioned activities (Gómez et al., 2021) that could very well be implemented in either of those classroom settings.

The main goals of the Gómez study were to examine how action while reading an informational text about physics can (1) enhance the learning of targeted vocabulary and (2) aid in the comprehension of such texts. This study was conducted with second and third grade children in Chile, thus extending our current knowledge to a different linguistic and social context. The participants in this study were 216 children enrolled in second and third grade in local schools in the greater Concepción, Chile, area. The children were native speakers of Spanish and did not have any learning disabilities as reported by their teachers.

Although examples in this chapter are translated into English, all the children were reading in Spanish. The text we used for the study was a book about Newton's laws of motion called *How Objects Move* (see figure 5.3). This book is one of several available on EMBRACE, an iPad-based application that follows the principles of embodied theory. (The application is described more thoroughly in Walker et al., 2017.) The *How Objects Move* text has a total of seven chapters, and each has about five to seven end-of-chapter comprehension questions. Vocabulary words are presented at the beginning of most of the chapters. These targeted vocabulary words appear underlined throughout the text and the children have the ability to tap on them and listen to the pronunciation whenever they need to do so. The text also has key sentences in blue font (see figure 5.3).

Children in control conditions were told that these sentences were particularly important and should be carefully attended. In the action conditions, the blue font signals the child to act out the sentence. When using the EMBRACE iPad application, acting out means moving pictures on the iPad screen to simulate the sentence. For example, for the sentence "When you pull the boat by the rope, the pulling force starts the boat moving," the child puts her finger on the rope in front of the boat and drags the boat through the pictured water.

We trained the children with two different types of embodied movement. The first one had the movement embedded within the EMBRACE iPad application



How do Objects Move?

What makes balls and rockets and everything else move? A force is needed to start an object moving, to stop it from moving, or to change direction. A force is like a push or a pull. **When you pull the boat by the rope, the pulling force starts the boat moving.**

Figure 5.3
Screenshot from chapter 1 of the EMBRACE text *How Objects Move.* (The application uses full color.) The children in Chile saw the text in Spanish.

as already described. The children moved the images on the screen to simulate the meaning of that sentence. The second type of movement used the children's own bodies to pantomime the targeted sentences in the text. In this condition, the children along with the experimenter acted out gestures to depict the meaning of the sentences. We included the latter condition to determine whether action while reading is effective outside of a technology context. It is unlikely that EMBRACE technology will be available to many schools worldwide, so it is important to demonstrate the efficacy of low-technology embodied activities.

In all, there were four conditions. In one condition, Child Reads + Action, the children read the text independently and used the iPad to simulate the sentences. In the Child Reads control condition, the child read using the iPad but did not move the pictures. In the Experimenter Reads + Action condition, the experimenter read the text aloud (with the children following along); in addition, for the sentences in blue font, the experimenter acted out the sentence (e.g., pantomimed pulling the boat by the rope), and the children did the same. In the Experimenter Reads control condition, again the experimenter read the text while children followed along, but there was no pantomime.

Children were randomly assigned to each of the conditions. We conducted this study during the regular school day, and to participate the children left their classrooms in groups of five. We gave the children a pretest with ten fill-in-the-blank sentences and ten target vocabulary words in a word bank (the words, translated into English, were force, friction, acceleration, gravity, direction, space, flame, laws, movement, and backward). Children were asked to complete the sentences using a word from the word bank. The same vocabulary test was used as the posttest assessment after the intervention, with the only difference being that the sentences were presented in a different order. To assess the children's comprehension of this informational text, every child answered multiple-choice questions in a hard-copy assessment packet. Children had to answer about five to seven questions at the end of each of the seven chapters.

Children participated in the intervention for two days. Before the first day, the vocabulary pretest was administered to all the participating children as a large group. On the first day of the intervention, the children read four of the seven chapters (and answered the after-chapter multiple-choice questions). On the second day of the intervention, they read the remaining three chapters and took the vocabulary posttest.

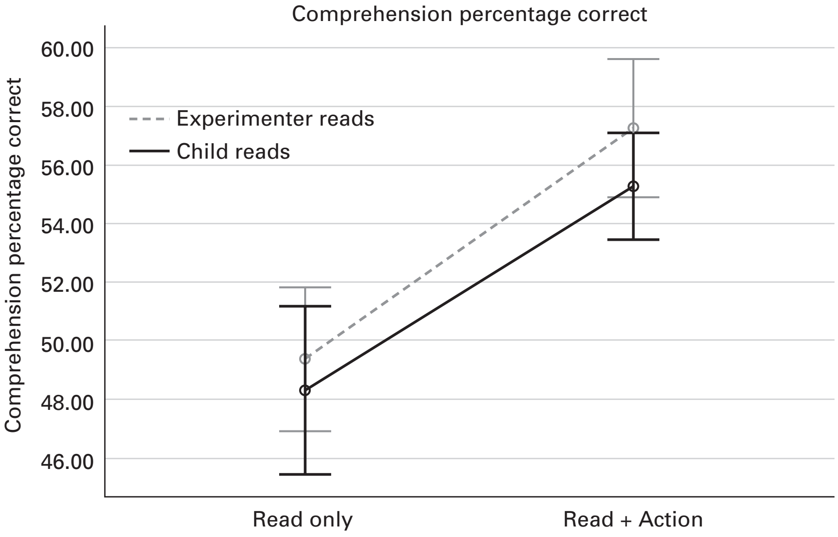
We conducted analyses of covariance using grade level (children were in two different grades) and the vocabulary pretest score as covariates. Our results showed that action, independent of technology, significantly enhanced both text comprehension and vocabulary learning.

Figure 5.4 presents the mean (adjusted for grade and vocabulary pretest) for the comprehension test. The Read+Action conditions resulted in greater comprehension than Read Only, with a moderate effect size of $d=0.44$. The difference between the Child Reads and the Experimenter Reads conditions was not statistically significant. Similar results were found for the vocabulary posttest (figure 5.5). That is, children learned more vocabulary by using the embodied actions than from reading alone, with a moderate affect size of $d=0.32$.

These results emphasize the importance of action and its application when teaching using informational texts in primary grades. Importantly, the use of an embodied reading approach is widely applicable in the classroom, especially when working in centers or small groups. The findings are especially promising for schools where technological resources may not be widely available. That is, even without technology, the implementation of a curriculum based on embodied principals is possible and strongly recommended.

Adult Learning of Foreign Language Vocabulary

Macedonia and colleagues have studied how gesture can facilitate acquisition of foreign language vocabulary words (e.g., Macedonia, 2014; Mayer et al.,

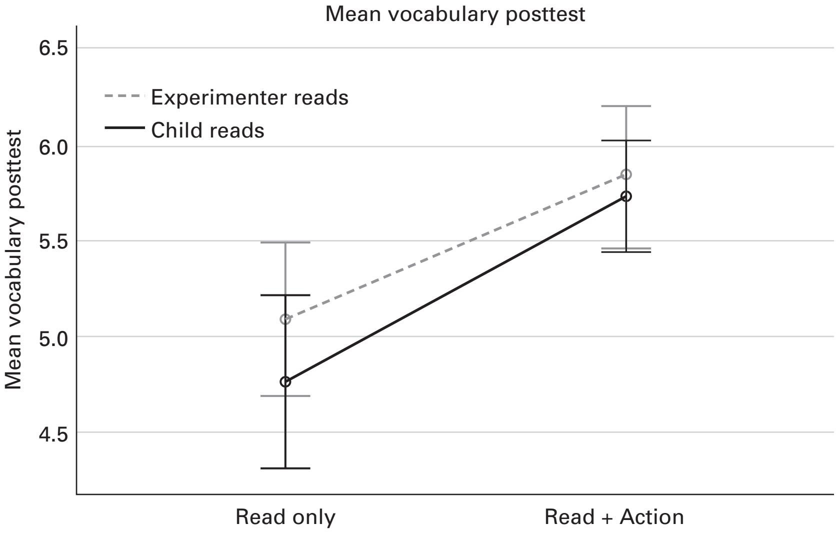


Covariates appearing in the model are evaluated at the following values:
Vocab Pretest = 2.93
Error bars: +/ – 1 SE

Figure 5.4
Text comprehension posttest scores from Gómez et al. (2021).

2015). Mayer et al. (2015) studied how adult participants learned foreign language/native language equivalents under three conditions. In the Verbal condition, the learner was only provided with the foreign words and their translations; in the Picture condition, the words and translations were accompanied by a picture (that the participants traced); and in the Gesture condition, the words were accompanied by a video showing a gesture that pantomimed the word and the participants performed the gestures. These procedures continued for multiple sessions until the translations were learned close to perfectly, and then long-term memory was tested two and six months later. Memory for the translations was significantly greater in the Gesture condition at both of the retention tests.

Immediately after the training trials (and before the long-term retention tests), the participants were also tested on the translation equivalents while their brains were being scanned using fMRI. The participants in the Gesture condition showed more activity in motor areas of the brain, and the participants in the Picture condition showed more activity in visual areas of the brain. Furthermore, the differential activity predicted performance on the translation tests (see Kontra et al., 2015 for similar results in learning concepts in physics).



Covariates appearing in the model are evaluated at the following values:
Vocab Pretest = 2.93
Error bars: +/– 1 SE

Figure 5.5
Vocabulary posttest scores from Gómez et al. (2021).

Thus, adult foreign language vocabulary learning can be facilitated by applying principles of embodiment. In particular, grounding the vocabulary learning in motor system and perceptual system activity enhances retention.

Adult Learning of the Abstract Mathematical Concepts

The work described so far has dealt with rather simple vocabulary learning—that is, associating a word with a relatively simple definition. But some concepts, such as regression to the mean, are difficult to define with a simple definition, and even if a simple definition is offered, it may include many terms that are themselves in need of definition. Nonetheless, principles of embodied cognition can be applied to help learning of these very abstract ideas. Indeed, this situation is representative of the teaching of abstract concepts such as "democracy," "angular momentum," and "transubstantiation."

We will not review research on this topic; instead we provide a video demonstration (see Glenberg, 2021; for a description of the video, see Glenberg et al., 2021). The demonstration shows one of us (AG) presenting a two-level lecture. On one level, the lecture is an exposition of the abstract statistical concept of regression to the mean. On the other level, there is a discussion of the principles of embodied cognition being used to teach the abstract concept. The lecture is meant as a proof of concept. That is, to the extent that the viewer (you!) learn the concept of regression to the mean, it demonstrates the validity of the principles.

As discussed in the video, three types of grounding are used. The first is what we have been discussing all along: using activity in the sensorimotor and emotional systems to ground simple concepts. An example in the video (starting after minute 15:00) is using the experiences of stepping on a bathroom scale (action) and observing the weight (perception) to ground the concept of measurement.

The second notion of grounding is to ground some concepts on others that are already grounded. Thus, stepping on the scale repeatedly and observing measurements that change slightly from observation to observation is used to ground the concept of random error in measurement. That is, the concept “random error” is not directly grounded in a simple action. Instead, the grounding is based on the already grounded concept of “measurement.”

Third, the video uses extended procedures to ground complex or abstract concepts (see Barsalou, 1999, 2008). In fact, the discussion of grounding the term “random error” demonstrates the idea of an extended procedure. Random error is difficult to ground in one measurement (standing on the scale once). Instead, it involves repeatedly standing on the scale with subtle changes in the location of the scale, how the person steps on the scale, and so on, so that the measured weight differs from observation to observation. Random error is injected into each measurement by those subtle changes.

Using an extended procedure is a common technique for grounding abstract terms and why the term seems abstract—the term refers to a procedure rather than an object or instance. Importantly, however, the components of the procedure are themselves grounded in sensorimotor and emotional system activity. As another example, consider how one might teach the concept “democracy.” Children might be introduced to the procedures of having an election by literally having candidates, ballots, and counting ballots. After the procedure is acted out, the child can be taught that in democracies, elections like these are used to choose representatives or decide issues. The video uses several extended procedures (in addition to that used to define random error) to illustrate regression to the mean.

Conclusions

Learning vocabulary is a matter of linking a word with its meaning. But what is meaning? Standard theories of cognition propose that meaning consists of symbols (e.g., words) connected by rules (e.g., syntax). Embodied cognition proposes that meaning comes from grounding symbols in sensorimotor simulations. Thus, learning vocabulary requires linking the word with relevant sensorimotor experiences. In this chapter we have reviewed research demonstrating that simple bodily experiences can help children learn words like "startle" and "force," and to learn foreign vocabulary. Additionally, using successive levels of grounding in extended procedures can help older students learn abstract concepts such as regression to the mean. In the hands of a creative teacher, the principles of embodied cognition can be used to design effective, memorable, and enjoyable curricula for any topic.

Acknowledgments

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6 Educational Applications of Enacted, Embodied Approaches to Language Comprehension

Michael P. Kaschak and Amanda L. McGraw

Embodied cognition refers to the idea that cognitive processes are grounded in the operation of our bodies, and our bodies' systems of perception, action planning, and emotional responding (e.g., Glenberg, 1997; Barsalou, 1999; Wilson & Golonka, 2013). Embodied cognition started to receive increased attention in the cognitive science literature in the mid-to-late 1990s (e.g., Barsalou, 1999; Glenberg, 1997). Even at this early stage in the development of the embodied approach to cognition, it was apparent that the ideas associated with embodiment had the potential to impact thinking about education. For example, the idea that action is important for learning has a long history in the study of education (e.g., Montessori, 1917, among others). Additionally, there is a literature in cognitive psychology suggesting that action has benefits for learning and memory (e.g., Engelkamp & Zimmer, 1994). Finally, one of the first "embodiment" studies to appear in the cognitive science literature was a demonstration that the learning of a new task (using a compass to orient toward different locations) was improved when the learners were able to observe an actor pantomiming the motor components of the task (Glenberg & Robertson, 1999). As demonstrated by the chapters in this volume, embodied cognition has made a number of substantive contributions to educational research over the past two decades.

Embodied approaches to language comprehension are centered around the idea that the understanding of language involves construction of sensorimotor simulations of the content of the linguistic input (e.g., Glenberg & Robertson, 2000; Kaschak et al., 2005). To illustrate, consider this sentence: *Michael saw Meghan kick through a pile of leaves.* The embodied approach suggests that understanding this sentence requires a sensorimotor simulation of the perceptual elements of the input (e.g., seeing a girl kicking leaves; seeing the leaves move through the air; hearing the sound of the leaves moving) and the action-based elements of the input (e.g., the action of kicking while you walk). Note that the sensorimotor activity during sentence comprehension need not be consciously accessible, and that it is not necessary that all elements of the sensorimotor experience are simulated in detail.

Support for embodied approaches to language comprehension comes from two major sources. First, studies employing a variety of behavioral techniques have demonstrated that (1) the comprehension of language about action affects the movement of the body (e.g., Masson et al., 2008; Glenberg & Kaschak, 2002; Zwaan & Taylor, 2006), (2) the comprehension of language emphasizing perception interacts with the operation of the perceptual systems (e.g., Kaschak et al., 2005; Meteyard et al., 2007), and (3) altering the ability to express emotions affects the comprehender's ability to process language about emotional states (e.g., Havas et al., 2010). Second, a host of studies employing electroencephalography (e.g., Mollo et al., 2016; Schaller et al., 2017;) and functional magnetic resonance imaging (e.g., Hauk et al., 2004; van Dam et al., 2010), and transcranial magnetic stimulation (Buccino et al., 2005) have shown that the neural systems involved in both perception and the preparation and execution of action are also active while comprehending language about perceptual or action-oriented information.

It should be noted that the embodied approach to language comprehension is not without its critics. For example, Mahon and Caramazza (2008; Mahon, 2015) have argued that much of the neuroscience evidence for embodiment can be interpreted as supporting the view that although language comprehension *can* recruit sensorimotor information, language comprehension is not *primarily* based in sensorimotor information (i.e., the simulations discussed previously are secondary to the comprehension process). In addition, recent studies have questioned the replicability of some of the benchmark experiments in the embodiment literature (e.g., Morey et al., 2021; Papesh, 2015; Rommers et al., 2013). However, it is beyond the scope of this chapter to address the criticisms of embodiment that have arisen, but we note them here so that the interested reader can explore a broader perspective on this literature.

Embodiment, Education, and Reading Comprehension

Before reviewing some of the specific embodied approaches to the improvement of reading comprehension in elementary school children, we first (briefly) consider some basic ideas about what it takes to acquire reading comprehension skill. One perspective is offered by the *Simple View of Reading* (Hoover & Gough, 1990). The *Simple View* suggests that reading comprehension has two components: decoding skill (i.e., turning the orthography on the page into phonological information) and language comprehension (e.g., the child's existing oral language comprehension skill). The extent to which a child becomes a successful reader will depend on the extent to which their decoding and comprehension skills are developed. A similar perspective comes from Seidenberg's (2005) *triangle model* of reading development. The triangle model proposes that children have already developed a relationship between phonology and semantics (i.e., the language comprehension component of the *Simple View*). Learning to read involves learning to link orthography to phonology (the decoding component of the *Simple View*) to access semantics, and later to link orthography directly to semantic representations. Both the *Simple View* and the triangle model presume that the beginning reader comes to the task with some degree of a developed comprehension system. Children learn to link their (auditory) linguistic input to the objects and events around them by having conversations (e.g., Clark, 1996; Tomasello, 2003). The crucial step in learning to read involves learning to translate between orthographic and phonological representations so that the child can bring their oral language skill to bear on interpreting written language.

Glenberg et al. (2004) report an early intervention aimed at using the principles of embodied cognition to improve reading comprehension in beginning readers. The logic behind their intervention follows the structure of the *Simple View* and triangle model: language comprehension relies on connecting linguistic elements (e.g., the words and phrases in the linguistic input) to sensorimotor representations (e.g., the perceptual or motor representations to which those linguistic elements refer). That is, the task of language comprehension is to use the linguistic elements in the input to access the relevant sensorimotor representations in order to create a coherent simulation of the situation that is being described. The link between linguistic input and sensorimotor representations develops naturally as children acquire language, as the language acquisition process takes place in the context of conversations about the objects and events surrounding the child and their conversational partner (e.g., Clark, 1996; Tomasello, 2003). As children acquire literacy skills, much of their effort is placed on learning to turn the orthographic symbols into sounds (e.g., Rayner et al., 2001). Simply focusing on the orthography-phonology link may lead to a situation where some children are not developing the sensorimotor simulations required to support good comprehension.

Glenberg et al.'s (2004) intervention was designed to encourage the simulation process by providing children with a physical representation of content of the text (e.g., if the children were reading about a farm, they would see a play farm set in front of them). At certain points in the story, the children were asked to either act out the content of the last sentence they read (e.g., if the sentence indicated that *The cow walked away from the barn,* the children would use the toys to act out the event), or (in a different experiment) to imagine acting out the content of the last sentence they read. Carrying out the actions and imagining doing so led to comparable improvements in comprehension compared with children who only reread the critical sentences in the story. It is important to note that the children in this study were in second grade, likely at the age where most would be competent decoders of simple written texts but still developing their comprehension skills. That is, the children were at a stage in their literacy development when they were likely to benefit from this straightforward intervention.

In the years since the publication of this initial study, Glenberg's research team has done a number of follow-up studies aimed at expanding on the idea that encouraging children to map the linguistic symbols to the sensorimotor representations needed for comprehension has benefits for the language comprehension process. For example, Glenberg et al. (2011) modified Glenberg et al.'s (2004) procedure in an intervention called "Moved by Reading." Glenberg et al. (2011) demonstrated that the action component of Glenberg et al.'s (2004) manipulation could be transferred to a computer environment (i.e., moving things on a computer screen rather than moving the real objects), and that manipulating objects on a computer screen leads to comprehension gains that are as strong as the gains observed when students manipulate real objects. In addition, Adams et al. (2018) showed that an action- and imagination-based intervention strategy (similar to that used by Glenberg et al., 2011) could be effectively used with dual-language learners. Gómez and Glenberg (chapter 5 in this volume) provide an overview of this work.

Our laboratory group has built upon the basic principles of Moved by Reading and other such interventions to develop an embodied reading intervention that we dubbed "Enacted Reading Comprehension" (ERC; Kaschak et al., 2017). ERC was designed to improve children's ability to understand different kinds of abstract text content.[1] The intervention was based around the abstract concept of "opposing forces" and the dynamics involved as different kinds of forces interact with each other (with some forces overcoming the other forces). The opposing forces idea was introduced in the context of understanding science texts, then expanded to the understanding of persuasive texts, and finally applied to the understanding of a novel whose plot revolved in part around different internal conflicts faced by the characters. ERC takes an abstract concept (opposing forces), grounds the concept in bodily movement, and then uses this grounding as the basis for supporting children's understanding of a range of text types. Kaschak et al. (2017) provide a detailed reporting of the ERC procedures.

Using embodied, sensorimotor representations to ground abstract concepts is well supported in the literature. Lakoff and Johnson's (1980) seminal work on metaphor sketched a broad proposal for how the understanding of abstractions such as *power* and *time* (among many others) was grounded in perception and action. For example, *power* could be understood in part using the up-down dimension (more power is up, and less power is down), and *time* could be understood as movement through space. Lakoff and Johnson's (1980) proposals have been supported by behavioral evidence showing that (for example) thinking about time involves spatial and action-related representations (e.g., Casasanto & Boroditsky, 2008; Sell & Kaschak, 2011), and by neuroscience evidence suggesting a link between the cortical structures representing time and space (e.g., Walsh, 2003). It was from such ideas that we developed the idea of using bodily movement to embody the concept of opposing forces, and to apply this to the comprehension of different sorts of texts.

The initial phase of ERC involved asking students to read popular press science texts. During the first week, third- and fourth-grade children read a book in small groups about earthquakes (Simon, 2006). While reading, the children were introduced to the idea of opposing forces in the context of talking about the movement of tectonic plates. For example, children were asked to uses gestures, by holding their hands out in front of their body, pressing the palms of their hands together, and then moving the hands in opposite direction (one hand toward the body, one hand away from the body) while still pressing their palms together. Such actions illustrated the opposing movement of the plates and helped to embody the mechanics of an earthquake at a strike-slip fault. Similar actions were used to embody the mechanics of different sorts of fault lines and earthquakes (e.g., subduction zones). Children were cued to execute the actions where appropriate during their reading.

During the second week of ERC, children read a second science text. Third grade children read about hurricanes (Simon, 2007), and fourth grade children read about tornadoes (Simon, 2001). Children at different grade levels read different books so that the reading level of the texts would be appropriate for their level of reading skill. The idea of opposing forces was continued in this part of the intervention, but here the opposing forces concerned the movement of air masses from areas of high pressure to areas of low pressure. Children again executed actions to embody the relevant opposing forces and to understand the dynamics through which these opposing forces generate hurricanes and tornadoes.

The second phase of ERC extended the idea of opposing forces to the processing of persuasive texts. Children were introduced to the persuasive texts by drawing a metaphorical connection to the dynamics of earthquakes: there are opposing sides of arguments (just as there are plates with opposing motion), and these press against each other until one of them ultimately wins. The children were taught to use hand and arm gestures to depict the opposing sides of the debate in a series of persuasive texts discussing age-relevant topics (e.g., should school uniforms be required?). They also completed a graphic organizer depicting a fault line, to make the argument-earthquake analogy more explicit.

The final phase of ERC involved reading Linda Sue Park's book *A Single Shard* (2001). We chose this book because there were many plot elements that revolved around internal conflicts faced by the characters. Consider the following example. Tree-Ear, the main character in the book, is working for a potter. The potters in his village are competing to produce their best work in an effort to secure a commission from the emperor. Tree-Ear commits to taking a sample of his potter's work to the emperor for judging. On his way to the palace, Tree-Ear is attacked by thieves who shatter the pottery he was carrying, leaving him with only a single shard of pottery to show the emperor. Tree-Ear now faces a dilemma—does he turn home because he has nothing of value to show the emperor, or does he continue on to meet his commitment to the potter? We introduced children to the idea that this sort of dilemma could be understood in the same way as the opposing forces at work in persuasive texts and in the same way as the opposing forces found in nature. The children were again shown how to use hand and arm movements to embody the conflicts faced by the characters. The movements were used at various points in the text.

Kaschak et al.'s (2017) exploration of ERC was intended as a design study (i.e., to show that the method works, not to show that the method has efficacy when compared with different sorts of control groups). Nonetheless, they report preliminary evidence that children who work through ERC show learning in the content domains (science reading, persuasive texts, and *A Single Shard*) on which they were instructed.

The general efficacy of ERC and its effect on broader reading skills were assessed in a subsequent study (Connor et al., 2018). The results suggested that ERC had educationally meaningful impacts on measures of vocabulary. Interestingly, ERC was not uniformly successful in producing gains in vocabulary—the largest gains were found with children who had lower pretest vocabulary scores, and there appeared to be a negative effect for children who had the highest levels of pretest vocabulary. These data suggest that interventions such as ERC may be of more benefit for younger readers and for struggling readers. Although this idea has not been directly tested, it may be that the actions performed while engaging in ERC take children who are otherwise successful comprehenders away from the successful strategies that they were already using.

Through the Florida State University's Reading for Understanding project, we have also created other interventions that contain embodied elements. For example, "Language in Motion" (LIM; Connor et al., 2014) uses many of the elements found in the Moved by Language paradigm to teach children about particular syntactic forms (such as the use of adverbs, or the use of passive constructions). Children are presented with visual depictions of the house in which a story takes place and objects (such as toy furniture) to move in order to represent the events in the story. Connor et al. (2018) found that LIM had benefits for broader measures of reading skill. As with ERC, the benefits seemed to particularly strong for children with lower pretest vocabulary scores.

Our review of the literature on embodied approaches to improving reading comprehension in young children has been selective. Nonetheless, it is our sense that these studies suggest that incorporating sensorimotor elements into the reading curriculum can result in intervention strategies that are successful on a proximal level (i.e., when children are assessed on the content of the intervention lessons themselves, such as the content of a story or understanding a specific linguistic form that is being taught) as well as on a more distal level (i.e., moving performance on reading comprehension measures that are not directly taught in the intervention, such as vocabulary).[2] In the final section of this chapter, we discuss some of the broader issues that surround incorporating principles of embodied cognition into the classroom.

Embodiment in the Classroom: Challenges and Outlook

Embodiment-based interventions have shown promise for improving children's reading comprehension skills. As we look to the future of these interventions, there are important questions that need to be addressed. For example, there are questions about whether embodiment-based interventions are practical for broad use in classrooms. In addition, there are issues to resolve about how embodied interventions might relate to the overall reading curriculum that is offered in the school system. We discuss these (and other) issues below.

Embodiment-based classroom interventions often require the use of a unique set of materials for the intervention lessons, ranging from toys and manipulatives (see the studies mentioned in this chapter; Gomez & Glenberg, chapter 5 in this volume; and Marquardt Donovan & Alibali, chapter 10 in this volume) to more extensive augmented and virtual reality technologies (see Johnson-Glenberg, chapter 15 in this volume). Whereas some of these materials are probably found in most classrooms (e.g., objects to be used as manipulatives), it is unlikely that classrooms would have all of the materials required to execute the interventions as designed. The need for materials and resources in embodied interventions raises practical concerns for the implementation of such interventions in classrooms, particularly in cases where schools are working under conditions of limited resources.

One way to address practical concerns about embodiment-based interventions will be to pursue a research program that identifies the intervention components that are necessary to achieve successful outcomes. As one example of this, Glenberg et al. (2011) have demonstrated that whereas Glenberg et al.'s (2004) intervention involved the use of specific manipulatives, similar gains can be achieved when the intervention is implemented on a computer (i.e., requiring no external manipulatives). By examining which interventions or intervention components require real action and manipulation of objects, and which might be accomplished in a virtual environment, embodied interventions can be designed to be as resource-light as possible. We believe that this will be a key step in the development of embodiment-based interventions, as these interventions may ultimately be most useful as a tool for teachers to use with children who are showing particular struggles with reading (e.g., see Connor et al., 2014, for a discussion of the need for a multipronged approach to remediating reading difficulties in children) rather than the full basis for a reading curriculum. To the extent that embodied interventions are deployed on a use-as-needed basis, it will be important for the interventions to be as resource-light and instructor friendly as possible. Some literature suggests that imagined action and computer-based action may be as beneficial to comprehenders as the physical manipulation of real objects (e.g., Glenberg et al., 2004; Glenberg et al., 2011). If these findings are borne out in studies exploring a broader range of reading contexts, they would suggest that the use of computers and imagination-based techniques may be a resource- and instructor-friendly way of bringing embodiment to the classroom.

Our speculation that embodiment-based interventions will be most useful as supplements to the traditional reading curriculum points to additional potential avenues for research. Embodiment-based reading comprehension interventions largely fall under the scope of what Compton et al. (2014) have called "quick fix" interventions—interventions that are designed to be of relatively short duration (e.g., five to ten weeks, for an hour or two a week) and comparatively easy for researchers and teachers to implement. The design of these interventions may make for an effective research strategy, but studies on such interventions often leave important questions unanswered.

Following some of the discussion in Connor et al. (2014), we highlight the following issues. As a starting point, we need to know whether embodiment-based interventions have long-range benefits for readers. The outcome of many interventions is measured shortly after the end of the intervention (e.g., within a week or two), and it is less clear whether the effects that are observed persist over additional weeks, months, or years. Gaining clarity on this issue will be important for determining the value added (or the lack thereof) for incorporating embodiment-based techniques into the reading curriculum. In addition, more can be done to understand the "dose" of embodied interventions (i.e., the duration in terms of weeks, and the amount of time required each week) that is needed to have a meaningful, lasting impact on children's reading. We can also assess the individual variability associated with embodied reading interventions. Connor et al. (2018) suggest that embodied interventions may not be equally effective for all readers (and may hurt some readers). This finding suggests that it may be fruitful to explore whether there are particular groups of readers (e.g., struggling readers, beginning readers, or English language learners) who would be more likely to benefit from an embodied intervention.

As a final direction for research, we can explore the synergies that might be created by implementing embodied interventions alongside other "nonembodied" interventions. It strikes us that a key ingredient to the success of embodied interventions is that the readers are provided with access to an accurate model of the world described by the text. The environment for action (whether real action, computer-based action, or imagined action) is created so as to guide the reader toward a representation of the text content that accords with what the author had in mind. It is well known that knowledge is crucial for the comprehension of texts (e.g., Kintsch, 1988), and that lacking the knowledge needed to successfully model the events described in the text can impair comprehension (e.g., Bransford et al., 1972). Thus, what may be the key ingredient of embodied interventions (giving the reader a coherent model of the text content) could likely be integrated into nonembodied approaches to reading instruction to create a more broad and versatile set of interventions.

We have clearly raised more questions than answers as we look to the future of embodiment-based interventions on reading comprehension. It is our sense that these questions will be among the critical questions to address as we contemplate the role of embodied cognition in shaping our educational practices. To the extent that the core concepts of embodiment can contribute to educational practice, these concepts should be implemented in ways that lead to lasting, real change in the growth trajectory of young readers' comprehension skills.

Notes

1. ERC was developed within the context of the Reading for Understanding (RFU) initiative that the Institute for Education Sciences funded in 2010.

2. Although these interventions bear the stamp of "embodied cognition," we note that the logic of the interventions is consistent with nonembodied views of reading, such as the *Simple View* and triangle model discussed elsewhere in the chapter. Whereas the cognitive science literature often suggests a divide between embodied and nonembodied approaches (e.g., Mahon & Caramazza, 2008), our view is that embodiment is largely consistent with what is known about the cognitive science and neuroscience of cognitive processing (see Glenberg, 2010, for an argument for embodiment as a unifying perspective in psychology).

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7 Reading, Writing, Technology, and Embodiment

Anne Mangen and Antti Pirhonen

The insights emerging from embodied (or 4E) cognition (Newen, et al., 2018) hold considerable promise for education, but thus far have had little impact. The widespread implementation of digital technologies in classrooms presents a timely occasion to remedy this situation. The increasing abstraction entailed in the transition from pen and paper to keyboards, and from reading in print books to reading on screens, warrants supplementing extant perspectives on learning and technologies as they are currently represented in curricula and educational policy documents. This chapter helps educators to rethink and redefine the role and meaning of technology in education broadly speaking, and describes how the use of digital technologies in the acquisition of basic skills like reading and writing specifically impacts learning from an embodied perspective. Drawing on examples from Nordic school contexts, we illustrate how 4E cognition can be pursued to benefit the learning experience in our digital age.

For us, as human beings, the skills of reading and writing are not innate—meaning, there is no genetic blueprint for reading or writing (Wolf et al., 2012). Whereas children normally develop the ability to speak and communicate by means of language socialization, both reading and writing require systematic training over an extended period of time to develop. Helping children learn to read and write is one of the major tasks of basic education. A recent study using functional magnetic resonance imaging found that both reading and writing are multisensory experiences (Smith et al., 2018). Yet the ongoing digitalization poses new challenges for researchers and schools concerned with students' literacy skills. As advances in technology in classroom applications become more mainstream, the way in which children engage in reading and writing is changing. Therefore, we argue that the theory of embodied cognition (4E) should be acknowledged when considering the strengths and weaknesses of various technologies in supporting different aspects of reading (e.g., low-level processes such as letter-sound correspondences, and high-level processes such as inference-based comprehension skills) and writing.

Literacy, Technology, and 4E Cognition

Reading and writing are not simply abstract phenomena of verbal expression and meaning-making but are tightly intertwined with applied technology. For example, whether it is a slate, pen and paper, or some digital device, both low and high forms of technology are always an integral part of the reading and writing processes and outcomes. Any technology employed to various reading and writing activities has affordances—that is, any technology, medium, or device offers a range of possibilities of interaction and meaning-making. These affordances depend on the materiality and the technical features of the device. For instance, the affordances of a print book make it available for browsing in a different way than an e-book, whereas the affordances of a digital text enable the reader to search for the location of specific words by using the search function.

At the same time offering possibilities and constraints on our interaction with the device, affordances necessarily affect the perceptual, cognitive, and sensorimotor engagement with whatever is being written or read (Gibson, 1979). The role and function ascribed to the technology is therefore contingent upon whatever view of learning is prominent at any time. The current transition from reading with traditional reading technologies, such as the codex, to reading with contemporary electronic devices illustrates how the act of reading is intimately connected with and intricately dependent on the entire human being. Therefore, the current discourse that pushes for digital technology regarding reading (i.e., hypertext, etc.) and writing has significant implications for relevant embodied pedagogical and reform policies (Mangen & Velay, 2010).

The emerging view of embodied cognition, commonly called 4E cognition, is embodied, embedded, extended, and enactive (Newen, et al., 2018). This view has been gaining considerable traction across several disciplines over the past couple of decades (Carney, 2020). As a corollary, any academic skill (e.g., reading and writing) is always contingent upon the body, the tools and technologies used, and the environment in which the activity takes place. For example, an instrument or technology is experienced as an extension of the mind, as is seeing through eyeglasses or contact lenses, talking on a cell phone, or walking with a cane (Clark & Chalmers, 1998).

As a result, such a view of cognition has important and potentially wide-ranging implications for education, curriculum, and policy (Fincher-Kiefer, 2019; Glenberg, 2008; Kiefer & Trumpp, 2012). Nevertheless, there are few indications that research findings from 4E cognition have found their way to classrooms, resulting in a misalignment between research and practice.

Digitalization and the Nordic Model of Education

Although digital technologies were adopted early in classrooms in Finland and Norway—two exponents of the widely acclaimed Nordic model of education—the resultant discourse on learning, reading, writing, and technology has been fundamentally at odds with findings from empirical research on 4E cognition. As an example, we will examine the Finnish National Core Curriculum and the justification of what was termed the "digital leap" (Saari & Säntti, 2018), and suggest alternative ways to frame the discussion of educational technologies in light of insights from 4E cognition.

Long the envy of the world, Finland used to have the best student achievement scores in the world. Finland's performance on the Programme for International Student Assessment (PISA), which measures academic achievement of fifteen-year-olds in seventy-three countries, was an outlier, ranking at the top or near top on assessments of reading, mathematics, and science (Välijärvi, 2002). In 2012, however, Finland's performance in PISA dropped quite significantly (Finnish Government, 2013), and the drop was in part attributed to an increasing use of digital technologies in school (Heim, 2016).

The National Core Curriculum is the foundation of local curricula. The same conflict is equally clear in the most recent version of the core curriculum (2014). Analyses of this version show the prominence of a *certain kind* of technology—namely, the implementation of information and communication technology (ICTs). An exploration of Norwegian curricula and policy documents before and after ICT have yielded the same impression: Haugsbakk and Nordkvelle (2007) observed how older technologies such as textbooks or audiovisual equipment are hardly mentioned, whereas references to ICT are abundant. Moreover, there are "surprisingly few concrete descriptions of how ICT could or should be employed" (p. 9). The authors argue that ICT is included primarily in an instrumentalist manner, emphasizing the "usefulness" and "significance" of using ICT. Considering its meager research basis and the significant bias of *digital* at the expense of any other type of technology, it is indeed worth asking about the decision processes behind privileging digital technologies for "future" or "innovative" learning.[1]

In response, Pasi Sahlberg, a Finnish professor of educational policy, has pointed to research showing that frequent use of digital technologies with young children is a cause for concern. Sahlberg added that screen time and cell phones were dominating students' lives and should be banned in primary school and monitored in secondary. He further added that screen time and the inconvenient consequences—psychological, social, and physical—have affected students' learning in schools, especially for reading, mathematics, and science, all which require concentration, attention, and perseverance to perform well.[2]

The rationale for implementing digital technologies in education is often rooted in an assumption that they make learning more engaging, motivating, and fun. Rarely, however, are such assumptions substantiated by reference to empirical research. For example, over the past three decades in Norway, Torgersen (2012) found no empirical evidence in educational policy documents and curricula to support ICT in relation to improved learning outcomes. Nevertheless, Norwegian educational curricula continue to emphasize the importance of using digital technologies in education across disciplines. Handwriting with pen on paper is being replaced by keyboarding, and digital study materials (e-books) are emphasized at the expense of print textbooks.

Several scholars have pointed to the lack of evidence in support of learning outcomes for the use of ICT in education. Most recently, Balslev (2020) examined a large corpus of white papers and politically commissioned evaluation reports on ICT in education over four decades (1983–2015). These sources display an abiding conviction that education and pedagogy can and should be improved by developing strategies that place digital technology at the center of learning. The research evidence of a positive effect of digital technologies on various aspects of learning, however, has been scarce (for reviews and meta-analyses, see, e.g., Bulman & Fairlie 2016; Tamim et al., 2011). In fact, the OECD report *Students, Computers and Learning* (2015) presented a number of findings that seem to undermine many prevalent assumptions regarding the application of ICT and learning: data have demonstrated no appreciable improvements in student achievement in reading, mathematics, or science in the countries that have invested heavily in ICT for education (OECD, 2015, p. 3).

Most importantly, the large-scale study found that students who reported using computers frequently (in school and for leisure) performed worse compared with those who reported only a moderate use of computers (OECD, 2015). As summarized by Andreas Schleicher[3] in 2017, "In a nutshell today, digital technology does more damage than it actually does good" (see Balslev, 2020, p. 14). Pointing to the infusion of technology into classrooms should give pause, as other factors are important in its implementation. Looking at these research findings on learning effects, and the continued—even increasing—digitalization of education must motivate a closer look at the rationale and rhetoric underlying the implementation of ICT in classrooms and suggest alternative ways to frame the discussion of educational technologies in light of insights from 4E cognition.

Heim (2016) writes that emerging research on how the internet affects the brain—and thereby learning—suggests three principal consequences: shallower information processing, increased distractibility and decreased concentration, and altered self-control mechanisms. This is a cautionary tale—the implementation of a disembodied technology into the curriculum has not rendered evidence-based improvements, and it begs the question: Why not? Understanding reading, writing, and comprehension according to the principles of 4E cognition requires a paradigm shift in education, starting with how disembodied "technology" is defined and implemented in schools.

Defining Technology

Technology is commonly understood as a means of using tools to enhance knowledge or skills to perform a task. A universal definition of the term, however, is hard to find. Rather, technology remains an ambiguous phenomenon, which can be approached from numerous perspectives (see Rooney, 1997). As such, regardless of the perspective, technology is seen first and foremost as an instrument. This has typically been the assumption when dealing with reading and writing technologies. Indeed, within current educational policy and curricula, reading and writing are viewed as acts of meaning-making, creative expression, and verbal communication that can occur in digital or analogue environments, by the use of pen on paper, or keyboard and multimedia resources. Yet, there is little regard for the different affordances that these technologies provide. Nor are the potential implications of the increasing abstraction entailed in the transition from codex/print book reading to screen reading or handwriting to keyboarding. Looking at such questions through the lens of 4E cognition, however, yields a very different impression.

All technologies have their own material affordances and sensorimotor contingencies, which frame and constrain our interaction with the device. For instance, a printed book affords browsing and dog-earing the paper pages, whereas a digital text affords searching for specified terms. The material affordances of the substrate of paper, combined with those of the pen(cil), provides the writer with different possibilities and constraints for writing and drawing when compared with a keyboard—whether mechanical or virtual. From the perspective of sensorimotor contingencies and embodiment, writing with one technology—such as a mechanical keyboard—is fundamentally different from writing with another—a ballpoint pen on paper.

As we will see later, there is empirical evidence that such “framing constraints” of different technologies affect core cognitive aspects of reading and writing—for instance, recall and comprehension. This crucial aspect of technology use for learning has received precious little attention in educational contexts, with disparate perspectives about the use of technology in the classroom (Richmond, & Jordan, 2018). In the policy documents and educational reforms, as well as in the theoretical discourses on learning that currently dominate the field of education, 4E cognition has been conspicuously absent (Ord & Nuttall, 2016).

Digital Technology

“Digital technology” is also an ambiguous core concept. Whether we read European Union policy papers on the future of education and learning, or on national curricula, high expectations about the opportunities of digital technology for learning abound. Upon closer scrutiny, we may indeed ask whence this focus specifically on digital technologies. “Digital” means conversion of information to digits—usually, ones and zeroes. In education, the terms digitization (originally, the process of conversion from analog to digital) and digitalization (the adoption of digital technology to some context) are used rather carelessly, and we frequently hear about “digital learning” (or e-learning or similar). Presumably, this refers to the application of some digital products in education contexts. Importantly, though, learning itself is far from digital because human information processing does not convert information to a binary system. Arguably, concepts like digital learning or e-learning are metaphorical expressions that can be claimed to be misleading (see Pirhonen, 2005).

Hence, the prominence of “digital” in today’s discourse on technologies in education is grossly misleading because the digitality of fashionable consumer products, such as the smartphone and the tablet, attempts to hide from us, the users. The progenitors of modern studies of human-computer interaction found the ideals of interaction with digital devices to be invisible (Norman, 1998), intuitive, and ubiquitous (Weiser, 1991). Indeed, interaction with smart technology was supposed to be so transparent that it would result in an illusion of reality—as if the user of the device was using the real thing, not its digital substitute. The digital nature of the hidden processes is usually only revealed in the error condition. When something goes wrong, a picture that looked real suddenly breaks down to small squares—we say that the picture pixelates. In educational applications, it is hard to imagine a scenario in which we wish the learner to notice that the underlying basic technology is digital in nature. The loose talk about digitalization of education thus appears to originate from marketing jargon rather than from analysis of educational needs and an understanding of how learning—including reading and writing—is a deeply embodied and multisensory process of interaction with technology.

Whereas paradigms of learning have undergone significant revolutions in the last few decades, the structure and underlying conception of learning entailed in educational applications—implemented with digital devices in particular—has remained astonishingly stable (Saari, 2019). For instance, distance learning applications still often rely on video conferencing, in which the focus is on the talking head of a teacher, or exercises whose structure resembles the structure of so-called programmed learning from the 1960s and 1970s. In general, it can be argued that if the focus of the design of educational applications is on technical issues, the applications hardly reflect the contemporary theoretical development of teaching and learning. Most importantly for the present context, the understanding of "learning" on which such applications are founded remains entirely disembodied and uninformed by recent insights from the domain of 4E cognition. Instead, and perhaps especially in the Nordic educational context, policies, pedagogy, and curricula remain strongly influenced by sociocultural and social constructivist approaches to learning (see, e.g., Balslev, 2020; Mangen & Schilhab, 2012). In such perspectives, the role of the body—and embodiment—is squarely defined in social, cultural, discursive, or ideological terms.

Writing on a keyboard has by now become the primary mode of writing for most people, including for students in schools. This is particularly the case in the Nordic countries, where digital technologies are abundant in education starting in elementary school (e.g., Elstad, 2016). Likewise, we now increasingly read by engaging with texts displayed on screens, and we navigate by swiping and tapping rather than by interacting with the substrate of paper. Digital technologies introduce a level of abstraction, in which texts—written and read—become immaterial and intangible.

Pen and paper are technologies that were created for reading and writing. Their user interface and functionality serve the writing and reading of human language. They have their limitations and shortcomings, just as with any other technology. Computers, in turn, were brought into education from offices and an industrial context. In industry, ICT-enhanced productivity has been praised as a revolution (Rifkin, 2013). The success of one technology in one context, however, does not guarantee its success in a completely different context. Seymour Papert (1980) suggests that the setting in which tools from industry were introduced into schools was simply declared, rather than designed, as "educational technology." With respect to writing, when computers with keyboards were introduced in offices, they replaced typewriters to enable faster and more efficient writing. It was therefore appropriate to imitate the typewriter's user interface and use the existing skills of office workers. For instance, the QWERTY style arrangement of a computer keyboard is inherited from the mechanical typewriters, in which it was appropriate for technical reasons (i.e., the personal computer as we know it is a result of its history in industry and mechanical engineering).

Reading as Human-Technology Interaction

When we read and write, we engage with technologies that have distinct user interfaces, affordances, and sensorimotor contingencies. Digitalization reveals the fundamentally embodied nature of reading and writing, beyond what has been covered in the research on discourse processing and language comprehension (e.g., Glenberg & Kaschak, 2002; Zwaan, 2014; for an overview of much of this research, see Fincher-Kiefer, 2019). When we read, and especially when we read longer texts, we typically hold the text—whether on an iPad, a Kindle, or in print—in our hands. When reading for study, moreover, we often hold a pen or pencil in our hands and annotate, write in the margins, or use the pen to follow the lines and help sustain focus. Empirical research on medium preference in study reading has found a persistent print preference (Baron, 2015, 2021; Mizrachi & Salaz, 2020; Rose, 2011): Students report that they like holding the text in their hands; they miss the feel of paper when reading on screens, and they have a feeling that they focus better with paper than when reading from a screen.

Recent research inspired by 4E cognition may explain the contribution of haptics and kinesthetics to cognition during reading and writing. The role of our hands, and the close connections between fine-motor movement, perception, attention, and cognition, can hardly be overstated (for excellent overviews, see Wilson, 1999; Tallis, 2003). As a corollary, learning may be contingent on the ways in which various technologies—paper and pens, keyboards and touch screens—cater to our embodied and multisensory engagement with the devices and implements. Concurrent evidence from a range of studies in neuropsychology and cognitive science serves to underscore the key role of 4E cognition in the acquisition of basic skills such as reading and writing.

When reading, we do not merely engage visually with the text on the paper or screens. Part of the experiential—attentional, perceptual, multisensory, embodied—process is also the texture and materiality of the substrate on which the text is displayed. The material affordances of this substrate form an essential part of the embodied engagement with the text during reading, and define the nature of our haptic and kinesthetic interaction with the text. The text on paper is physically contiguous with its medium/substrate, whereas this contiguity between the substrate and the medium is split up in a digital device. Hence, when we hold a book, we "hold the material substance of the only text it can be," whereas when we hold an iPad or an e-reader, we hold "a virtual library, an archive, a media access tool, and so the device seems immaterial, abstractly functional" (Mc Laughlin, 2015, p. 177). Moreover, books are fundamentally multisensory objects in ways that screens are not (Spence, 2020).

Writing as Human-Technology Interaction

Analogously to reading, writing is not merely an "inner," perceptual, and cognitive process of text production and edition. Nor is it merely a sociocultural practice, or an act of creative or personal expression. It is all of this and more. Most importantly, writing always implies the use of some technology both in terms of the act of writing something and in terms of the (visible; tangible) result of one's writing—whether the lines and traces are on paper or the virtual text is on a screen. Insights from embodied cognition reveal how the embodied engagement with the technology used for writing is closely entwined with cognitive and experiential aspects of the result—the text. "Our knowledge about letter shapes is not solely visual . . . we also know how to write them" (Longcamp et al., 2003, p. 1492).

Learning to write has, until fairly recently, entailed meticulous fine-motor training to automatize the optimal trajectories of lines, curves, and dots that make up each single letter in the alphabet. With the introduction of digital technologies and keyboards, this part of beginning writing instruction has, in many schools, changed dramatically. Given the fundamental motor differences between writing by hand and by keyboard, it is not surprising to find evidence of the role of sensorimotor contingencies of writing devices (pen[cil] vs. keyboard) on aspects such as recognition and memory (for an overview of much of this research, see Mangen & Balsvik, 2016).

Handwriting entails setting up and, with practice, automatizing a specific motor program for each letter (the direction of strokes, lines, and curves is not accidental), and to create the perceptuomotor links that emerge through the creation of each letter. The movements entailed in writing a letter by hand completely define the shape of only that particular letter. When writing by hand, the information derived from producing, for example, the letter "g" (or "G") leaves a motor trace that supports subsequent visual recognition of the letter (including variants of it). By contrast, writing the same letter by typing it on a keyboard entails a pointing and tapping movement that, motorically, is close to identical to that entailed in producing the letters that are located next to “G” on the keyboard. In contrast, the “motor trace” of keyboarding consists in the proficient incorporation of the spatial distribution of letters across the keyboard (see Mangen & Velay, 2010).

A number of studies have evidenced the ways in which this feedback supports aspects of visual recognition, recall, and categorization of letters, both in children and adults (e.g., Longcamp et al., 2005; Longcamp et al., 2008; Mayer et al., 2020). A few studies have found similar results—that is, better recall after having written by hand than by keyboard—on a word level (e.g., Mangen et al., 2015) and on the level of short stories (Frangou et al., 2018). Hence, if curricula were premised on insights from 4E cognition, we might have seen a more nuanced approach to the implementation of digital technologies for reading and writing in education.

Discussion and Conclusions

Investments in education have been vital for the Nordic countries in the pursuit of welfare. Here, education is considered to be the nucleus capable of producing national identities, citizenry, and citizen ideals that distribute equal rights and opportunities among the entire population (Ydesen & Buchardt, 2021). The recent trends in policy-making, however, yield an impression that in certain countries—like Finland—the educational system as the bellwether of society has lost its status and become a mere instrument of supporting industry.

Available technology is the unavoidable precondition to the organization of education. The current COVID-19 pandemic made this point very clear: when the schools were temporarily closed as a precaution, the usual technological facilities, like school buildings and the technology inside them, were not available. The teachers had to reorganize everything in a couple of days’ time, only counting on the technology that they assumed their pupils had access to. Suddenly technology was at the very center of discussions about schooling.

Reading and writing are both fundamentally technical skills—there is no reading or writing without an appropriate technology. Thus, what kind of processes are actually activated during reading and writing largely depends on technology. For instance, whether writing with a fountain pen or typing with a computer keyboard, we say that we are writing, even though the processes are quite different due to different technologies.

Pedagogy, as central as it should be, is finally not a discrete object of development. Pedagogy can only be developed in terms of applied philosophy and available technology. Although education in Nordic countries is supposed to be research based, it is interesting that according to our analysis the usage of certain kind of technological products (ICT) lacks empirical evidence of its appropriateness.

In order to understand the push of digital consumer products into schools, we need to recognize that as soon as technological products are introduced, politicians will propose they be applied in education. The problem is that these persons apply their own, colloquial conception of learning and teaching. For instance, conditioning as the theoretical basis of learning was effectively discarded at least four decades ago, yet the bulk of learning applications on the web still appear to repeat behavioristic models with their structure, immediate feedback, and rewards.

After decades of intensive piloting, application, and research of digital educational technology, we still lack credible indication of the superiority of digital devices in education (e.g., Balslev, 2020; Cuban, 2001; Selwyn, 2014). Given the cost of all these efforts and the lack of evidence of their benefits in education, we conclude that educational objectives have not been the driving force of the computerizing of schools. It appears that certain patterns of failure are repeated when introducing technology in the school context (see Balslev, 2020; Cuban, 1986; Winner, 2009). Moreover, it can be argued that these patterns concern our cultures in general, not only education. For instance, the concern about the education equity crisis referred to as the “digital divide” (EdTrust, 2020) has been one argument for the introduction of digital devices in schools.

An expert in multimedia processing and learning, Richard E. Mayer (2009), pointed to the driving force—and the cause of the subsequent failure—of so-called educational technologies being the assumed power of the technology rather than an interest in promoting human cognition.

Summary

Because technologies are inevitably present in practically all learning processes, technological choices are crucial in the development of educational policies and practice. From the point of view of 4E cognition, this implies that the technological aspects of learning environments should be exposed to criteria that are based on the assumptions of cognition as embodied, embedded, extended, and enacted. Attention needs to be paid to the different affordances that these “technological instruments” provide. This approach challenges us to develop educational technology, which provides opportunities to create and manipulate physical, tangible objects and encourage the learners to throw themselves into that creative process we call learning.

In this chapter, we addressed some important and hitherto neglected issues concerning digital reading, with special emphasis on the vital role of our bodies, and in particular our fingers and hands. Reading is a multisensory activity, entailing perceptual, cognitive, and motor interactions with whatever is being read. With digital technology, reading manifests itself as being extensively multisensory—both in more explicit and more complex ways than ever before. The different affordances of paper and screen as substrates for reading and writing illustrate the core of the 4E thesis: how 4E opens a perspective very different from the Cartesian dualism in the analysis of reading and writing processes.

To be prepared for the next wave of educational technology, efforts in the implementation of 4E cognition to school practices could be the awaited counterweight to the pressures from outside the educational context. Well-informed teachers should be able to make objective-driven choices among technologies rather than blindly pursuing a modern look in their classrooms—or just opposing everything new (see technophobia, Brosnan, 1998).

Notes

1. In the case of Finland, one clue could be the composition of an expert group of the educational use of ICT, nominated by the government (Finnish National Board of Education, 2010). The group consisted of twenty-three members. The chair of the group was the then director of the National Board of Education. The other twenty-two members represented the National Board of Education (one member), the Ministry of Education (one), municipal organizations (two), universities (three), the Finnish Funding Organization for Technology and Innovation (one), the Information Society Development Center (one), the Trade Union of Education in Finland (one), and—most interestingly—enterprises (eleven). In other words, half the members participated to promote their businesses. In popular media, the work of the group was reported as an expert view of what our educational system requires at the moment. It was not surprising that the central recommendation was a huge investment in ICT by schools (e.g., Liiten, 2010).

2. Should schools ban smart phones or teach self control? School News Australia, May 30, 2018; https://www.school-news.com.au/news/should-schools-ban-smart-phones-or-teach-self-control/

3. Schleicher is Division Head and coordinator of the OECD Programme for International Student Assessment (PISA) and the OECD Indicators of Education Systems programme (INES).

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III

STEM

8

Seeing Is Achieving: The Importance of Fingers, Touch, and Visual Thinking to Mathematics Learners

Jo Boaler

Sometimes there is a research finding that is such a surprise—conveying a result that is so far from the realms of what seems possible—it causes cognitive dissonance. The extent to which finger knowledge predicts a person's achievement in mathematics is one of those areas of research. This result becomes easier to understand when it is placed within the broader research literature emerging from neuroscience, showing that our brain processes mathematics with the help of two visual brain pathways. This chapter shares some of the compelling and important new research around visual and physical experiences with mathematics as well as some activities and resources that teachers and parents may use to help students benefit from this important knowledge.

Most people think of the mind and the body as completely separate entities, with the mind holding knowledge and abstractions, and the body passively taking ideas from the mind to the physical world. But embodied cognition researchers point out that many of our mathematical concepts are held in visual and sensory motor memories.

Embodied cognition researchers note the ways in which people posture, gaze, gesture, point, and manipulate their writing tools as evidence that mathematical ideas are represented (in part) in the motor and perceptual areas of the brain (Nemirovsky et al., 2012). Indeed, people often draw shapes in the air, using space around us to "spread out" our ideas. For example, we may decide that one side of a table represents an idea and point back to it when we want to refer to that idea, even though there is nothing actually there—just our previous motions designating the space (Alibali & Nathan, 2012). Researchers have concluded that the body is an intrinsic part of cognition: the parts of our brain that control perception and the movement of our bodies are also involved in knowledge representation (Hall & Nemirovsky, 2012). It is fairly well known that knowledge of dance or sport is held in sensory motor areas of our brain, yet many would be surprised to learn that mathematics knowledge is also held in sensory motor memories.

Finger Perception and Mathematics Understanding

Ilaria Berteletti and James R. Booth (2015) showed that the "somatosensory finger area" of the brain, an area thought to represent finger sensation, helps with finger representation of ideas even when fingers are not being used. The researchers found that when eight- and thirteen-year-old students were given complex subtraction problems, the somatosensory finger area of their brain was activated, even though the students did not use their fingers. The researchers also found that this finger representation area was involved to a greater extent with more complex problems that involved higher numbers and more manipulation.

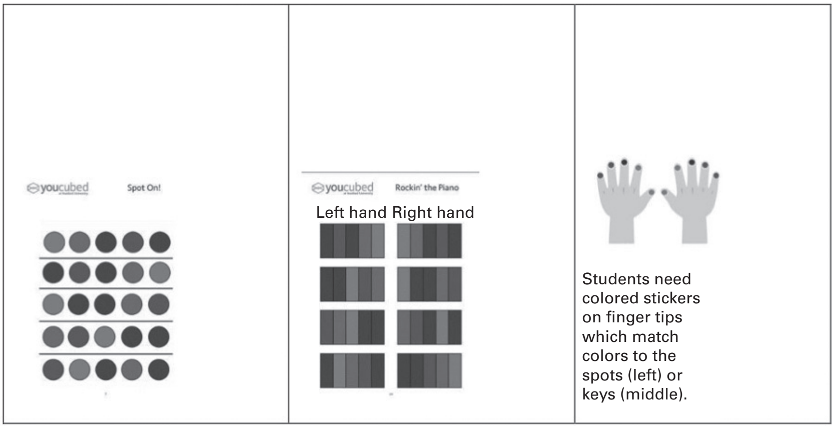
Evidence from both behavioral and neuroscience studies shows that when people receive training on ways to perceive and represent their own fingers, they develop better representations of their fingers, also known as "finger perception," which leads to higher mathematics achievement (Gracia-Bafalluy & Noël, 2008; Ladda et al., 2014). Researchers found that when six-year-old children improved the quality of their finger perception, they improved in arithmetic knowledge, particularly subitizing (the ability to recognize a number in a set without counting), counting, and number ordering.

In an eight-week experimental intervention, Stanford researchers found that first-grade students who used a robotic device that helped develop finger perception, with students using fingers to choose answers to mathematics problems and receiving haptic feedback in their fingers, improved their mathematics achievement to a greater extent than a similar group of students working on the same questions with a computer (Martinez et al., in press).

Penner-Wilger & Anderson (2013) found that even university students' finger perception predicted their scores on calculation tests. She also found that finger perception in grade 1 predicted students' achievement on number comparison and estimation in grade 2 (Penner-Wilger et al., 2009). Researchers assessed whether children had a good awareness of their fingers by touching the finger of a child—held under a desk or book so the child could not see which finger was being touched—then asking them which finger was being touched.

There is clear agreement among neuroscientists that the development of finger perception is important for mathematics achievement, yet debate exists about why this is the case. As neuroscientist Brian Butterworth has pointed out, "without the ability to attach number representation to the neural representation of fingers and hands . . . numbers themselves will never have a normal representation in the brain" (1999, pp. 249–250).

One of the recommendations from neuroscientists is that schools focus on *finger discrimination*—developing students' abilities to distinguish between different fingers. The researchers not only have pointed out the importance of



Students need colored stickers on finger tips which match colors to the spots (left) or keys (middle).

Figure 8.1
Some different examples of finger activities on Youcubed.org.

number counting on fingers for brain development and future mathematics success, but they also advocate that schools help students discriminate between their fingers. This seems particularly significant because neither schools nor curriculum have traditionally paid attention to this kind of finger-based work. Instead, many teachers have been led to believe that finger use is babyish and to be moved past as quickly as possible (see Boaler, 2019). Fingers may be a student's most useful visual aid—critical to mathematical understanding and brain development—that endures well into adulthood. Similarly, the presence of good finger perception among musicians is now thought to be an important part of the reason that musicians often display higher mathematical understanding (see Beilock, 2015). Neuroscientists recommend that fingers be regarded as the *functional link* between numerical quantities and their symbolic representation, and an external support for learning arithmetic problems.

We have drawn upon such knowledge to provide adapted exercises to train children in finger perception. The Youcubed Team, a Stanford center dedicated to giving research-based mathematics resources to teachers and parents, has used such knowledge to create engaging classroom and home activities for young students, which are provided free on Youcubed.org (see figure 8.1; see also the resources section).

The Multidimensional Nature of Understanding

The research on the importance of finger understanding becomes less surprising when it is placed within other research on the visual pathways, which are important for mathematical work and understanding.

Our brains are made up of "distributed networks," and when we handle knowledge, different areas of the brain are activated and communicate with each other. When we work on mathematics in particular, brain activity is distributed between many different networks, which include two visual pathways: the ventral and dorsal visual pathways (see figure 8.2). Neuroimaging has shown that even when people work on a number calculation such as 12 × 25, with symbolic digits (12 and 25), our mathematical thinking is grounded in visual processing.

A widely distributed brain network underpins the mental processing of mathematics knowledge (Menon, 2014), which includes dynamic communication between the brain systems for memory, control, and detection and the *visual processing regions of the brain.* The dorsal visual pathway has reliably been shown to be involved when both children and adults work on mathematics tasks (see figure 8.2). This area of the brain particularly comes into play when students consider visual or spatial representations of quantity, such as a number line (figure 8.3).

Number line knowledge has been shown in cognitive studies to be particularly important for the development of numerical knowledge and a precursor of children's academic success (Siegler & Booth, 2004; Hubbard et al., 2005;

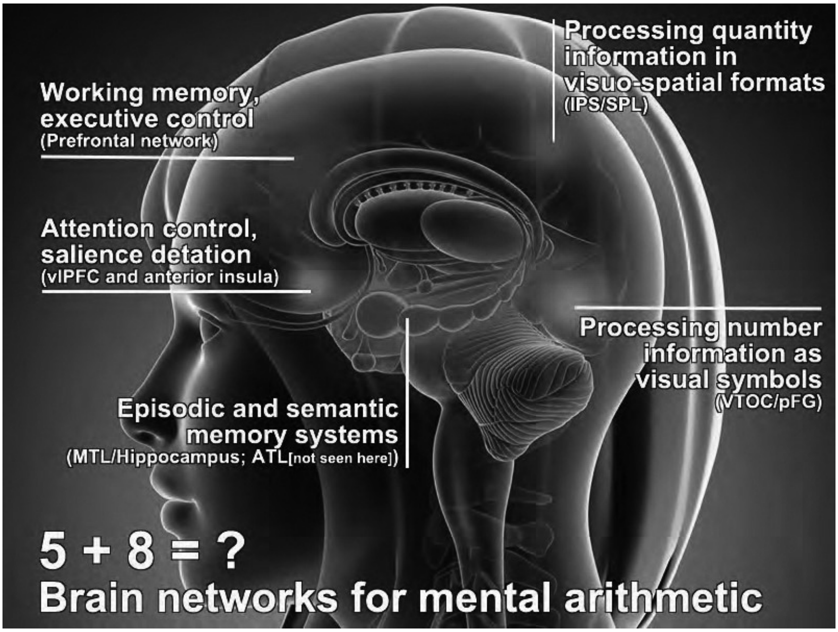

Working memory, executive control
(Prefrontal network)
Processing quantity information in visuo-spatial formats
(IPS/SPL)
Attention control, salience detation
(vlPFC and anterior insula)
Processing number information as visual symbols
(VTOC/pFG)
Episodic and semantic memory systems
(MTL/Hippocampus; ATL[not seen here])
5 + 8 = ?
Brain networks for mental arithmetic

Figure 8.2
Brain networks for mental math. Source: Lang Chen.

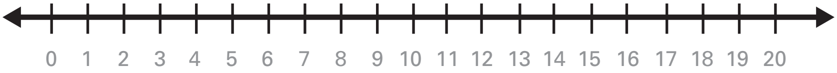


Figure 8.3
A number line.

Kucian et al., 2011; Schneider et al., 2009). Not only are mathematics learners helped by seeing mathematical ideas visually, but also an important part of brain development comes when different brain pathways communicate with each other. When a student sees a problem numerically, and they also depict the idea visually, communication occurs between brain pathways. Researchers even found that students from low socioeconomic backgrounds were achieving at the same levels as students from higher socioeconomic backgrounds after just four fifteen-minute sessions of using a number line (Siegler & Ramani, 2008).

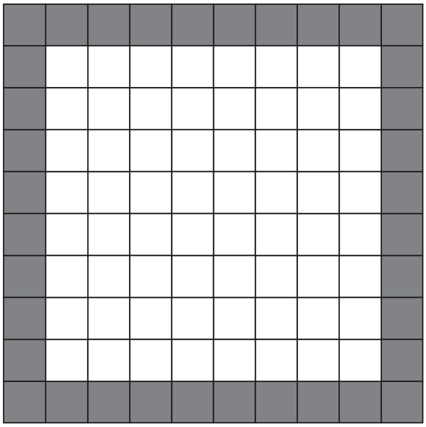
The frontal networks, the medial temporal lobe, and, importantly, the hippocampus are also important brain areas within the "mathematics" network (see figure 8.2). In a recent study, when regular people were compared with particularly successful "trailblazing" people, it was found that the successful people had more communication between brain pathways (see Boaler, 2019a). This suggests that our students should experience mathematics in a more multidimensional way, with multiple opportunities to see and experience mathematics in different ways—through numbers, but also through touch, seeing, drawing, building, and writing in words.

Classroom Examples

In the following section, I describe how the Youcubed Team has developed a middle-school summer mathematics experience for students. Students in this program spend approximately thirty hours, or eighteen lessons, experiencing mathematical ideas visually and creatively.

In our own teaching of the summer camp, we found that students increased their achievement on standardized tests by the equivalent of 2.8 years of school, after eighteen lessons (see also Boaler, 2019b). At the end of the teaching, the students described their experiences as transforming their views of mathematics and, importantly, their own potential.

As part of our summer teaching we taught algebra as a visual subject as well as a numerical and symbolic one. Algebra classes are often dedicated to students rearranging symbols, and students approach important mathematical concepts such as functions through numbers and symbols without any visual understandings. In one activity, for example, we asked students to look briefly at a border



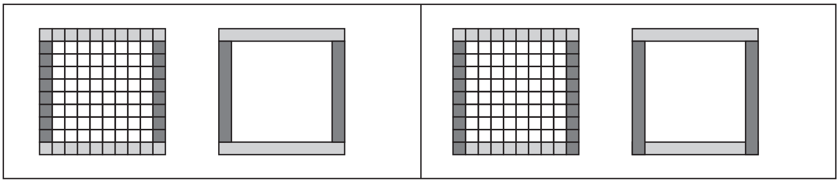


Figure 8.4
An example of an activity from YouCubed. Note the difference in the patterns ■ and □. The students thought about the number of squares in the border in many different ways, which they described at first numerically, then though words, and then algebraically.

around a square, and we asked them to work out how many squares were in the border without counting them (figures 8.4 and 8.5) (see also Boaler & Humphreys, 2005). The students' different ways of seeing were a resource for developing the students' understanding of functional relationships and algebraic equivalence.

In a different lesson we asked the students to consider distance-time graphs, an area of mathematics that is notoriously challenging even for college students (Clement, 1989). We invited the students to learn about distance, time, and velocity by physically walking the line of a distance-time graph, using a motion sensor that tracked their movement. The students stunned district visitors when a girl gave a perfect explanation of the graphing of velocity, rejecting a common misconception that is held by millions of students. When the students explained the concept, they gestured with their hands to show the movement, again showing that their understanding of the concept was held in sensorimotor memories.

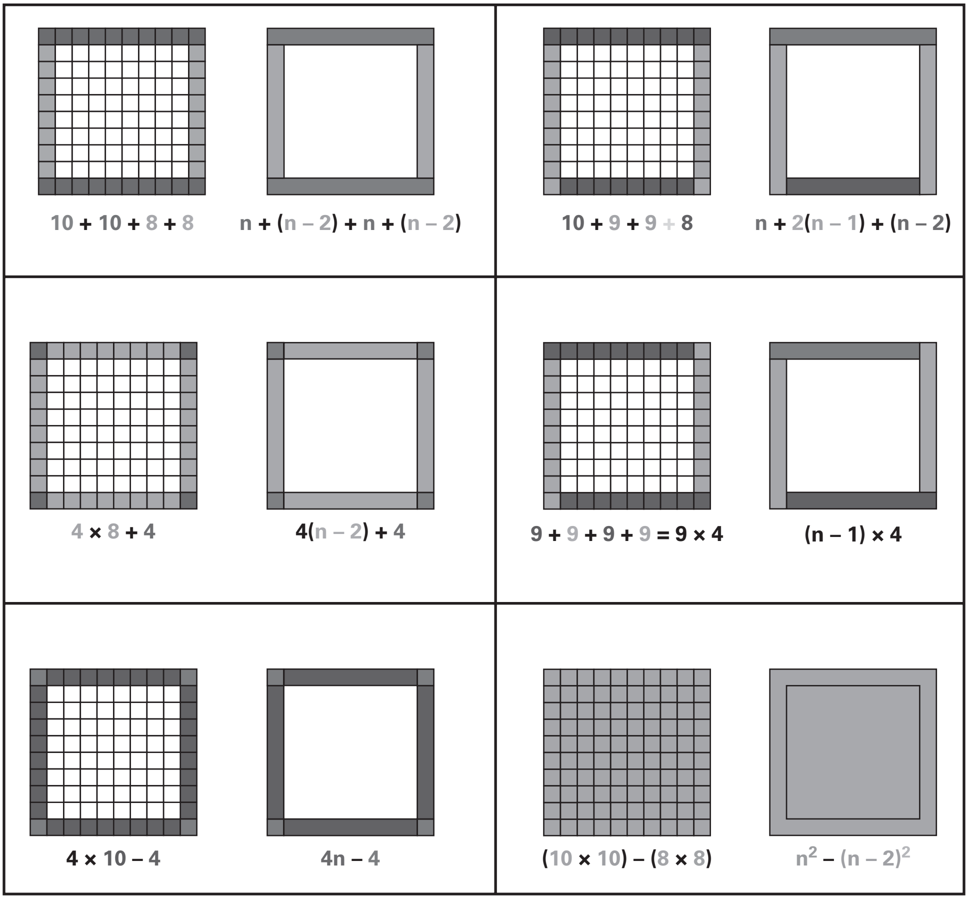


Figure 8.5
A continuation of the activity in figure 8.4 from Youcubed.

To engage students in productive visual thinking, our students were asked, at regular intervals, how they *saw* mathematical ideas, and they were asked to draw what they were seeing. One of the students' reflections at the end of one of our mathematics camps was

> It's like the way the way our schools did it, it's like very black and white. And the way people do it here [in summer camp], it's like very colorful, very bright. You have very different varieties you're looking at. You can look at it one way, turn your head, and all of a sudden you see a whole different picture.

The teaching of velocity through movement was clearly powerful for the students, and motion is a helpful resource for students in reaching depth of understanding (see Boaler, 2019a, and Youcubed.org).

When mathematics classrooms focus on numbers, status differences between students often emerge to the detriment of classroom culture and learning. Some students state that work is "easy" or "hard" or announce they have "finished" after racing through a worksheet. But when the same content is taught visually, the status differences that so often beleaguer mathematics classrooms often disappear. Thomas West has noted the equalizing effect of visual work with adults, describing the time that various experts from academic disciplines came together to think visually, showing mutual respect toward each other and to different ideas, in ways that rarely happen when work is numerical (West, 2014). It seems possible that visual mathematics may contribute to equitable outcomes—valuing students' thinking in different ways as well as encouraging deep engagement.

In my teaching of Stanford undergraduates, I introduce mathematics problems to them saying, "I don't care about speed. In fact, I am unimpressed by those who finish quickly—that shows you are not thinking deeply. Instead, I would like to see interesting and creative representations of ideas." After a few lessons the students start to broaden their views of mathematics and begin to create different insightful representations, along with new understandings of ideas.

Conclusion

The evidence I have reviewed—showing the distributed, visual, and physical nature of mathematical understanding—seems particularly significant when considering that mathematics, for most students, is taught as a series of numbers and abstract concepts. It is probably not surprising that so many students feel that mathematics is inaccessible and uninteresting when they are plunged into a world of abstraction and numbers. Most curriculum standards and published textbooks do not invite visual thinking. Many textbooks provide pictures, but they do not invite students to think visually or to draw their own representations of ideas. When textbook and classroom approaches do encourage visual work, it is usually encouraged as a prelude to the development of abstract ideas rather than a tool for seeing and extending mathematical ideas and strengthening important brain networks.

The new knowledge that we have, showing the visual processing of mathematical ideas, may explain the many research studies indicating that the teachers who emphasize visual mathematics and who use well-chosen manipulatives encourage higher achievement for students, not only in elementary school (e.g., Reimer & Moyer, 2005) but also in middle school, high school, and college (Sowell, 1989). Entire volumes from the Mathematical Association of America have been devoted to the encouragement of visual mathematics in college (see, e.g., Zimmermann & Cunningham, 1991). The visual K-12 mathematics lessons created by our team at Youcubed are downloaded and used in every state across the United States and in approximately two-thirds of US schools. In surveys completed by teachers and students, 88 percent of teachers say they would like more of the activities, and 83 percent of students report that the visual activities enhance their learning of mathematics.

Despite the prevalence of the idea that drawing, visualizing, or working with models is something only for young children, some of the most interesting and high-level mathematics is predominantly visual. Mathematician Maryam Mirzakhani contributed important new mathematical ideas though visual mathematics. Visual mathematics can also come from abstract mathematics and can extend the ideas to much higher levels. They can also inspire students and teachers to see mathematics differently—to see the creativity and beauty in mathematics and to understand mathematical ideas.

Years ago, workplace knowledge was based on words and numbers, but our new knowledge of the world is based largely on images that are "rich in content and information" (West, 2014). Most companies now compile large amounts of data, known as "big data," and the fastest growing job of the future is the task of making sense of that data, including seeing data patterns visually. Computer scientists and mathematicians at Stanford and elsewhere now *see* patterns in data that could never have been picked up by numerical techniques (for more detail see https://www.youcubed.org/resource/data-literacy/).

Some scholars note that it will be those who have developed visual thinking that will be at the top of the class in our new high-technology workplaces that increasingly draw on information visualization technologies and techniques in business, technology, art, and data science (West, 2004, p. 17). In our education system it is important not to prioritize any type of learner over others—or even to give the idea that it is productive to take one learning approach and focus upon it. The new neuroscience supports this approach—students should be encouraged to develop mathematical thinking through visuals, numbers, symbols, models, movement, and words and draw the connections between them. This is twenty-first century learning that invites teachers and students to see mathematics as the subject it really is: a beautiful, creative set of connected ideas that empower.

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9

Groups That Move Together, Prove Together: Collaborative Gestures and Gesture Attitudes among Teachers Performing Embodied Geometry

Kelsey E. Schenck, Candace Walkington, and Mitchell J. Nathan

Mathematics is a particularly notable domain in which to understand the role of body movement for improving reasoning, instruction, and learning. One reason is that mathematics ideas are often expressed and taught through disembodied formalisms—diagrams and symbols that are culturally designed to be abstract, amodal, and arbitrary (Glenberg et al. 2004)—so that these ideas are regarded as objective and universal. This stems from a Cartesian view of knowledge that separates mental experiences from physical experiences and ways of knowing (Lakoff & Núñez, 2000; also called the "romance of mathematics," p. xv). This Cartesian "duality" carries forth to the various fields touched by mathematics that also strive for objectivity and universality—topics as vast and diverse as the physical and social sciences, business, civics, and the arts. There is a growing appreciation, however, that for effective education, mathematics must be meaningful to novices and that this can occur by *grounding* the ideas and notations to learners' physical experiences and ways of knowing (Nathan, 2012).

Grounding can occur when an abstract idea is given a concrete perceptual referent so that it is more readily understood (Goldstone & Son, 2005). One way that ideas can become grounded is through gesture. Gestures are spontaneous or purposeful movements of the body that often accompany speech and serve as a way to convey ideas or add emphasis to language as well as mathematics (Goldin-Meadow, 2005).

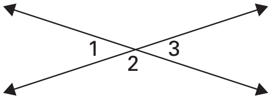
Gestures can act as a grounding mechanism by indexing symbols and words to objects and events, and by manifesting mental simulations of abstract ideas using sensorimotor processes (Alibali & Nathan, 2012). The grounding of novel, abstract ideas and notational systems through gesture, action, and material referents is part of the emerging framework of grounded and embodied cognition. *Grounded cognition* is a general framework that posits that formal notational symbol systems and the intellectual behavior are "typically grounded in multiple ways, including simulations, situated action, and, on occasion, bodily states" (Barsalou, 2008, p. 619).

Nathan (2014) positioned mathematics learning at the intersection of three influences: (1) content, such as numbers and operations, algebra, and geometry; (2) disciplinary practices, such as executing procedures and forming proofs; and (3) the psychological processes, such as spatial imagery and logical deduction, for engaging in disciplinary practices with specific content. The learning experiences are quite different whether from a Cartesian or embodied frame. Consider two experiences for fostering geometric reasoning (figures 9.1 and 9.2).

Figure 9.1, a traditional two-column geometry proof, is a common display from which students (and teachers) are expected to gain an understanding of how to prove that opposing angles formed by intersecting, coplanar lines are always equal. The vertical angles theorem (adapted from proposition 15 of Euclid's *Elements, Book 1*) is widely applied throughout geometry, art, and engineering. The proof poses many obstacles to understanding the content and disciplinary practices, however. The diagram is rich with highly formalized terms, such as $\angle 1$ and $m\ \angle 1$. Unstated assumptions bound, such as $m\ \angle 1$ and $m\ \angle 2$, can be arithmetically added—they are each quantities—but $\angle 1$ and $\angle 2$ are labels that cannot be combined. Another is that operations such as those performed in line 4, which are presented as static, declarative statements—here, the transitive property of equality—hide the processes that enact these

Given: $\angle 1$ and $\angle 3$ are vertical angles.

Prove: $\angle 1 \cong \angle 3$



	Statements		**Reasons**
1.	$\angle 1$ and $\angle 3$ are vertical angles.	**1.**	Given.
2.	$\angle 1$ and $\angle 2$ are supplementary $\angle 2$ and $\angle 3$ are supplementary.	**2.**	Angles that form a linear pair are supplementary.
3.	$m\angle 1 + m\angle 2 = 180$ $m\angle 2 + m\angle 3 = 180$	**3.**	The sum of the measures of supplementary angles is 180.
4.	$m\angle 1 + \boldsymbol{m\angle 2} = \boldsymbol{m\angle 2} + m\angle 3$	**4.**	Transitive property of equality
5.	$m\angle 1 = m\angle 3$	**5.**	Subtraction property of equality
6.	$\angle 1 \cong \angle 3$	**6.**	Angles with the same measure are congruent.

Figure 9.1
Two-column proof for the vertical angles theorem.

operations. Most students experience geometry as an amodal topic, disconnected from the sensory systems of the body. It is little wonder that for many students high school geometry is not only poorly understood but an obstacle to advanced studies in math as well (Szydlik et al., 2016).

Figure 9.2 investigates similar content (geometry) and disciplinary practice (proof) through an embodied approach. Rather than static propositions that presuppose logical deduction, we observe psychological processes using body movement and extended social cognition in the form of collaborative gestures to ground the mathematical ideas (Walkington et al., 2019). Instead of a two-column proof, these teachers are engaged in a construction of *transformational proof* (Harel & Sowder, 1998), in which universal claims are investigated using logic in addition to operating directly on the mathematical objects themselves to establish their generality.

Embodied approaches emphasize meaning-making over matching to disciplinary practices. Several scholars have shown that student learning is enhanced when teachers adopt appropriate instructional gestures in their practices (e.g., Alibali et al., 2013; Cook et al., 2008). Unfortunately, teachers and curriculum developers do little to embrace embodied approaches; teachers often exhibit naïve views about the role of the body in mathematical thinking and teaching

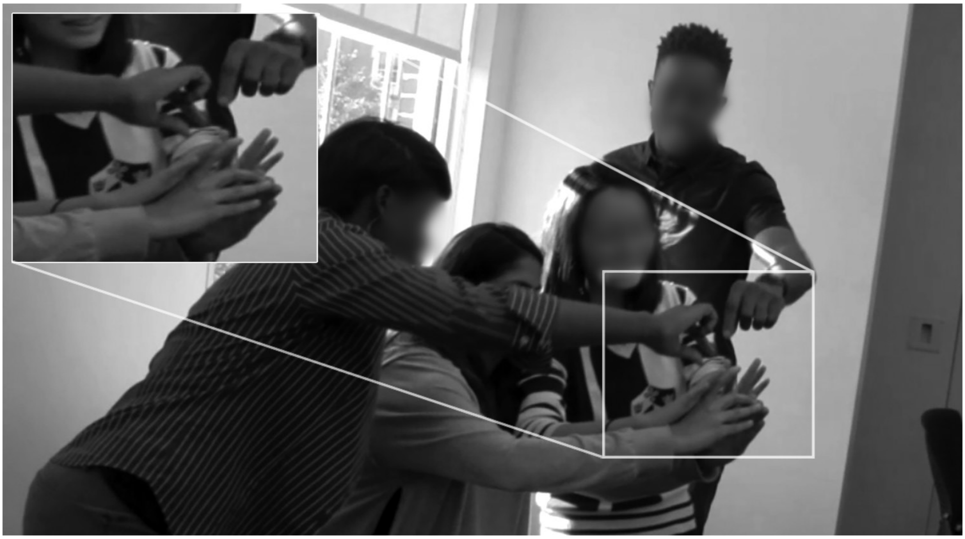


Figure 9.2
Forming and transforming mathematical objects collaboratively. Investigating the *inscribed angle* conjecture, “the measure of the central angle of a circle is twice the measure of any inscribed angle intersecting the same two end points on the circumference of the circle.”

(Walkington, 2019). As one teacher put it when asked how the body can be used in math learning, "I haven't really thought about this . . . I assume some students are kinesthetic learners, so movement can help with memory. I also think movement throughout the day helps students stay active and awake." Another reports, "They can use their fingers to count, their feet for measurement, their hands to use manipulatives and draw picture stories." Accordingly, commercial programs such as *Action Based Learning Lab* (https://www.youthfit.com/abl), *MATHS DANCE* (http://www.mathsdance.com), and *Math in Your Feet* (Rosenfeld, 2016) promise "optimal learning" using "brain research" to improve math teaching and learning. As inspiring as these body-based interventions may sound, there is a dearth of rigorous, empirical evidence of their effects on learning and teaching. Few resources for teacher professional development exist that communicate effective strategies for adopting embodied approaches for the teaching and learning of mathematics.

There is a lack of solid research for understanding when and how teachers will adopt embodied teaching practices. Like many new educational practices, we recognize that widespread adoption of embodied instructional practices that use gesture and movement will depend on more than research showing their benefits in laboratory and classroom studies. For teachers to take up new practices, such as effective use of gestures for learning and instruction, the new practices must be presented in ways that are commensurate with teachers' beliefs about learning and instruction and the new practices of interest (Putnam & Borko, 2000). Professional development designers must also understand the role of teachers' content knowledge, pedagogical content knowledge, and teachers' attitudes toward mathematics (Hill et al., 2008).

These needs are discussed in the context of an illustrative case we present in this chapter. In the context of this case, we discuss the relationships between teachers' attitudes about instructional gestures and their actual gesture usage while solving problems. We also discuss how teachers' gesture use during mathematical reasoning is influenced by the collaborative context and describe how gesture production predicts the quality of one's mathematics arguments. Together, these elements form the necessary groundwork for informing future teacher professional development experiences that can bring embodied mathematics practices to scale.

Theoretical Background

The theory of gesture as simulated action (GSA) (Hostetter & Alibali, 2008) posits that gestures arise during speaking when premotor activation, formed in response to motor or perceptual imagery, is activated beyond a speaker's current gesture threshold. This threshold can vary depending on factors such as the current task characteristics (e.g., spatial imagery), individual differences (e.g., prior knowledge), and situational considerations (e.g., instructional context). Hostetter and Alibali (2019) review the evidence that gesture threshold is influenced by cognitive skills, personality, and culture as well as the perceived importance of the information being communicated. They speculate that beliefs about gesture (e.g., whether it is polite) may also influence gestural tendency. GSA is not an account of instruction: therefore, from our perspective, the role of social context and beliefs about the influence of gestures on learning is underspecified in the current theory.

Teachers often use gestures during mathematics instruction (e.g., Alibali & Nathan, 2012; Valenzeno et al., 2003). Teachers can use pointing gestures to indicate different aspects of a diagram or call attention to physical objects and their properties, beat gestures to emphasize particular words or phrases, and representational gestures to directly model mathematical objects, shapes, or relationships using their hands. Studies suggest that teachers use gestures to provide scaffolding (Alibali & Nathan, 2007), and that student learning can benefit when teachers gesture (Valenzeno et al., 2003; Goldin-Meadow et al., 1999). A substantial body of empirical research shows that teachers can modulate their use of gestures to foster learning gains (e.g., Nemirovsky & Ferrara, 2009; Pier et al., 2014; Sinclair, 2005). Students also use gestures to aid their mathematics learning (Alibali & Nathan, 2012; Rasmussen et al., 2004), and gesture use is sometimes correlated with more cogent mathematical reasoning (Cook & Goldin-Meadow, 2006; Goldin-Meadow, 2005; Nathan et al., 2020).

In the realm of education, two important qualities of gestures have emerged. The first is how gestures provide information that is redundant (matched) or complementary (mismatched) to the accompanying speech (Church & Goldin-Meadow, 1986). Pedagogically, children and adults notice information uniquely expressed with mismatched gestures (Kelly & Church, 1997), and learning can benefit more from instruction with gesture-speech mismatches compared with instruction with matched gestures or no co-speech gestures (Singer & Goldin-Meadow, 2005). The second quality is the conditions under which teachers engage in *collaborative gestures,* defined as communicative movements that are physically and semantically co-constructed by multiple interlocutors during social learning interactions in service of learning and instruction. Specifically, collaborative gestures build off the gestures of interactional partners (Walkington et al., 2019).

The illustrative case we present examines teachers' use of gestures during collaborative proofs about geometric conjectures in relation to their attitudes about the role of gestures for learning. Proof is a ripe area for investigation, as it is “a richly embodied practice that involves inscribing and manipulating notations, interacting with those notations through speech and gesture, and using the body to enact the meanings of mathematical ideas” (Marghetis et al., 2014, p. 243). With this chapter, we seek to address the following questions: (1) How are teachers’ gesture behaviors during proof activities associated with their attitudes and beliefs about the role of gesture in learning? (2) When participating in groups, how are teachers’ gesture behaviors associated with the number of collaborators and gesture usage by collaborators? (3) Does group-level collaborative gesture behavior correlate with quality of mathematical reasoning?

To answer these questions about teachers’ use of gestures, we present data from a study with fifty-three preservice and in-service teachers enrolled in a variety of math education courses. Of these participants, 62.3 percent were in-service teachers.

Additionally, 41.5 percent of participants indicated they teach or plan to teach elementary school (grades K-5), 34.0 percent of participants indicated middle school (grades six to eight), and 24.5 percent of participants indicated high school (grades nine to twelve). More detail about the participants and methodology can be found in Walkington et al. (2019). Teachers were arranged in groups to play a video game, *The Hidden Village,* which was designed to support learners’ embodied approaches to proving and disproving middle and high school geometry conjectures (Nathan & Walkington, 2017) (figure 9.3). During the game, the teachers collaboratively produced proofs for up to eight mathematical conjectures. We video-recorded teachers, and we coded both their gestures and the accuracy of the proofs they produced during game play, with each instance of a teacher group proving one conjecture being considered separately.

One important consideration when looking at gestures during mathematical problem-solving is whether gestures are *individual* (i.e., the gesturer made a gesture that was not triggered by or related to the gestures of others) or *collaborative* (i.e., the gesture was spurred by the gestures of others). Collaborative gestures can represent a potentially powerful form of embodied mathematical reasoning. We also determined whether the teachers’ proofs were correct by determining whether the proof (1) was generalizable and held for all cases under consideration; (2) utilized logical inference, progressing through an inferentially sound chain of reasoning, where conclusions are drawn from valid premises; and (3) exhibited operational thought, where the prover progresses systematically through a goal structure, anticipating the outcomes of the proposed transformations (Harel & Sowder, 1998).

Finally, we initially gave all the teachers a survey that assessed their beliefs about gesture, the Teacher Attitudes About Gesture for Learning and Instruction (TAGLI) survey (Nathan et al., 2019). This survey assesses whether

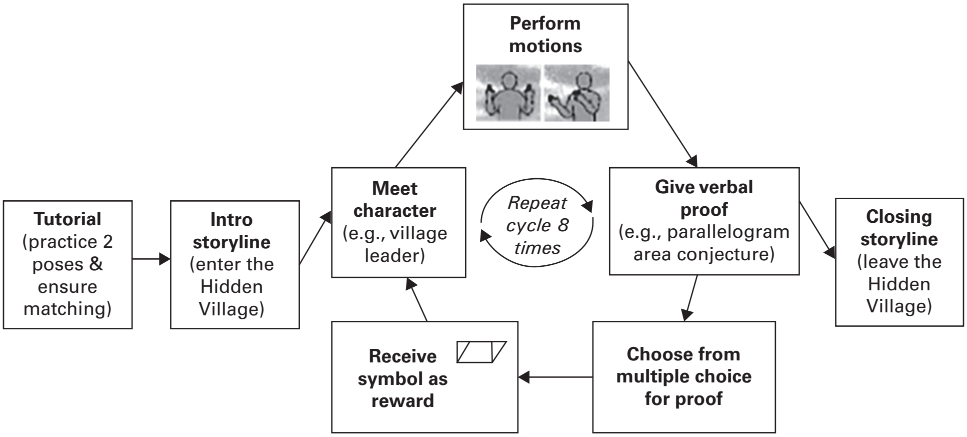

Perform motions
Tutorial (practice 2 poses & ensure matching)
Intro storyline (enter the Hidden Village)
Meet character (e.g., village leader)
Repeat cycle 8 times
Give verbal proof (e.g., parallelogram area conjecture)
Closing storyline (leave the Hidden Village)
Receive symbol as reward
Choose from multiple choice for proof

Figure 9.3
Flow of game play for *The Hidden Village.* After an initial tutorial that addresses where to stand and body calibration (box on far left), the game introduces the storyline that the player is a lost traveler who has stumbled into the Hidden Village. Players must interact with the characters (eight in all) who are engaged in village activities (cooking, crafts, etc.) by matching the in-game character movements. With each character, players are prompted to evaluate the truth of a mathematical conjecture and provide a justification for their choice and make a multiple-choice selection, all of which are recorded via audio and video. Players then receive a reward symbol and more area of the map of the village is revealed, indicating players' progress toward leaving the village.

teachers believe (1) gestures benefit classroom learning, (2) gestures are distracting, (3) gestures influence learning because they are redundant, (4) gestures influence learning because they are complementary to the accompanying speech, (5) instructional gestures are due to unconscious processes, and (6) instructional gestures are under conscious control, as well as items addressing the reasons teachers think people gesture, the perceived causes of gesture efficacy, and the frequency of gesture use. We used logistic regression models to perform quantitative data analysis using these variables.[1]

Point 1: Teachers Often Gesture While Solving Math Problems Together

Gestures were ubiquitous in our study as the teachers explored, discussed, and solved problems together. In particular, while they were proving conjectures, we found that teachers made an individual gesture 52.6 percent of the time and made a collaborative gesture 31.5 percent of the time. Figure 9.4 compares two groups of teachers proving the *two sides* conjecture. In the left panel, we see an instance where one group member makes an individual gesture that her group mates do not build upon. In the right panel, we again see one teacher making an individual gesture, but then it is built upon in another teacher's gesture and mirrored in a third teacher's gesture.

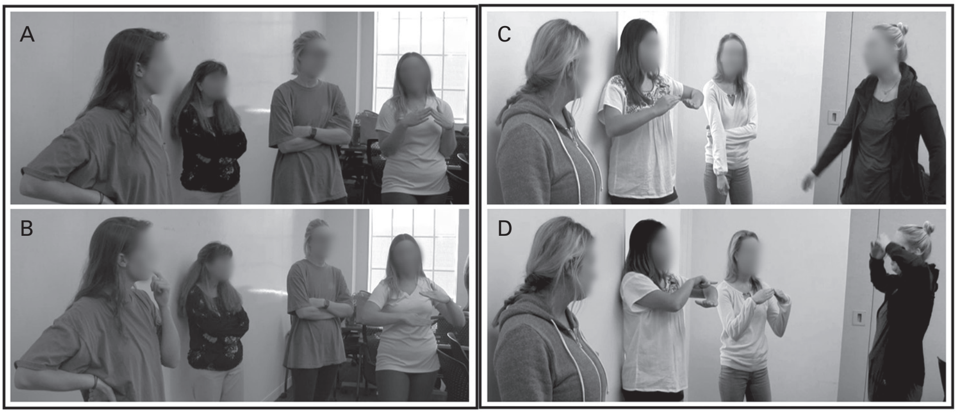


Figure 9.4
Two groups proving the two sides conjecture: "the sum of the lengths of any two sides of a triangle is always greater than the length of the remaining side." In the first group, Mary (far right) is performing two individual gestures as she explains to her group members (A and B). In the second group, Karen (middle left) is performing an individual gesture (C). Kristi (far right) collaboratively builds upon Karen's gesture while Tanya (middle right) mirrors Kristi's gesture (D).

Point 2: Teachers of Different Grade Levels May Have Different Gesture Tendencies

We also found that middle school teachers were more likely to gesture than elementary school teachers. There was a marginal difference in the same direction between elementary and high school teachers. It would make sense that middle and high school teachers, who usually teach only mathematics and may have stronger content preparation in mathematics, might gesture more when solving math problems than elementary teachers who are often generalists. Figure 9.5 shows a group of middle school teachers proving the *opposite angle* conjecture. The middle school teachers make a series of alternate and build collaborative gestures to explain that when the length of the side of a triangle increases, the angle across from the side will widen in order to complete the triangle.

Point 3: Teachers' Attitudes about Gesture Can Have Associations with Whether They Actually Gesture

We also found that teachers who indicated that gestures are distracting and interfere with learning had a lower relative chance of gesturing while proving conjectures. This finding makes sense because if you believe your gestures are distracting, you might be less likely to use them when collaborating. Surprisingly, however, teachers who indicated that gestures were effective because they elicited attention and made connections also had a lower relative chance of gesturing. This finding goes in an unexpected direction (i.e., is a negative effect when it might be expected to be a positive effect). For collaborative

[1] Cynthia: So like the side… so angle A is like bigger than angle B. So the side opposite angle A will be bigger than the side opposite angle B.

((A. Cynthia draws her finger diagonally from a point representing an angle to where the opposite side of the triangle would be and then repeats the motion from the other direction))

[2] Bree: Oh. Yeah. Because it's wider.

((B. Bree spreads her hands apart horizontally a few times))

[3] Cynthia: Yeah.

[4] Bree: Yeah.

[5] Cynthia: Because it's a wider angle.

((C. Cynthia makes an angle with her hands moving vertically. Bree anticipates and makes the same gesture))

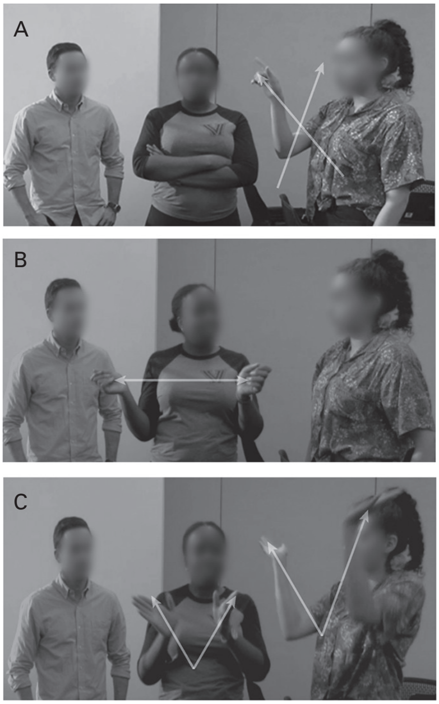


Figure 9.5
A group of middle school teachers performing collaborative gestures while proving the opposite side conjecture: "if one angle of a triangle is larger than a second angle, then the side opposite the first angle is longer than the side opposite the second angle." Cynthia is on the right, and Bree is in the middle.

gestures, the results showed that indicating on the TAGLI survey that gesture had a positive effect on instruction was positively associated with performing collaborative gestures.

Point 4: The Characteristics of Collaborative Groups Can Be Associated with Tendency to Gesture

In our study, being in a smaller group while proving the conjectures together seemed to be associated with individual teachers using more gestures. The same relationship held for individual teachers' tendency to use collaborative gestures while solving problems. We also found that teachers were more likely to make collaborative gestures if other members of their group were gesturing, too. Figure 9.6 shows how during the *reflection rotation* conjecture, a group of three each performed their own individual gestures then a series of collaborative gestures. This small group of three teachers performed four individual gestures and three collaborative gestures during this short exchange.

((A. Hayley and Rebecca individually gesture after reading the conjecture aloud. Hayley draws an "R" in the air while shaking her head. Rebecca rotates her right hand away from her left hand.))

[1] Megan: No, because that flips it and you have to rotate it 180 degrees for it to flip.

[2] Hayley: Yeah. Absolutely.

[3] Rebecca: Right for it...yeah.

((B. Megan makes a flipping motion with pointer finger up and away from her body. Rebecca repeats her rotation gesture in anticipation. Hayley mirrors Rebecca's gesture))

[3] Megan: A triangle would be the way to prove this because with a square, you might not be able to tell.

[4] Hayley: Yeah. I always think of an "R".

((C. Hayley redraws an "R" in the air, then rotates her palm))

[5] Rebecca: Oh yeah, yeah. Because then you can like move...yeah.

((D. Rebecca again repeats her rotation gesture but larger in response to Hayley's gesture))

[6] Megan: That's a good idea. That's a good way to prove it. I really like that.

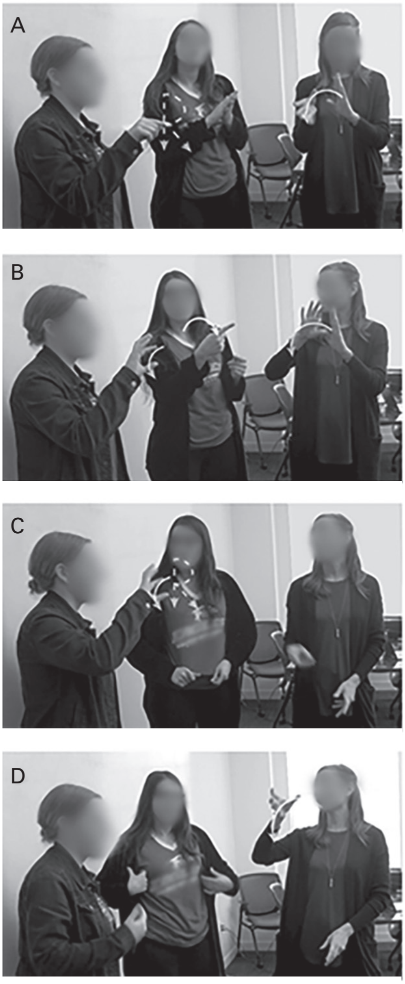


Figure 9.6
A small group of teachers performing individual and collaborative gestures while proving the rotation reflection conjecture: "reflecting a point over the *x*-axis is the same as rotating it 90 degrees." Hayley is on the left, Megan is in the middle, and Rebecca is on the right.

Point 5: Collaborative Gestures Have Potentially Powerful Associations with Valid Mathematical Reasoning

Our study also suggested that as teacher group members made more collaborative gestures, they increased their relative odds of getting their geometry proofs correct. The likelihood of participants producing an accurate mathematical proof (per trial, per group) was 51.8 percent. Making gestures in general that were not necessarily collaborative, on the other hand, did not predict correct proofs. This

[1] Cynthia: Yeah, because a parallelogram is just slanted.

((A. Cynthia draws right arm horizontally across her body while leaning right, then repeats leaning motion))

[2] John: Yeah.

[3] Carole: Is it the same?

((B. Carole holds up two thumbs and index fingers at 90 degree angles and then twists them slightly))

[4] Bree: Yeah 'cause a parallelogram is length times width.

((C. Bree draws finger across horizontally then vertically then horizontally. She did this same gesture silently while Carole was talking above, and was not observing Carole))

[5] John: Yeah, basically if you move… like if you cut off a triangle.

((D. John makes a vertical cutting motion in the air))

[6] Cynthia: Oh, put it on the other side.

((E. Cynthia makes upside-down "U" motion, right hand))

[7] John: And like put it on the other side, it would be the same.

((F. John makes upside-down "U" motion with right hand))

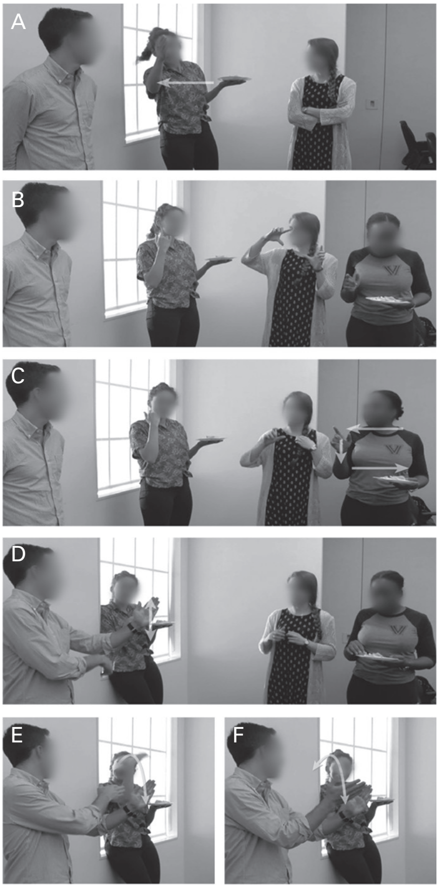


Figure 9.7
A group of teachers performing a series of alternating and anticipation collaborative gestures while proving the *area parallelogram* conjecture: "the area of a parallelogram is the same as the area of a rectangle with the same length and height." In the first image, John is on the left, Cynthia is in the middle, and Carole is on the right. In the second image, Bree is on the far right.

suggests that collaborative gestures might be particularly important to group members' understanding of geometric conjectures. Figure 9.7 shows a group of four in-service middle school mathematics teachers working through the *area parallelogram* conjecture using a series of alternating and anticipation gestures while discussing the veracity of the conjecture, which ultimately leads to a correct proof. Each of the four group members participated in collaborative gestures that both built on arguments when the participants were in agreement, and redirected arguments when a disagreement occurred.

Discussion and Implications

The illustrative case presented in the previous section helps to provide some insights in answering important questions about teacher gesture. Working backward from important educational outcome measures, we learned that making more collaborative gestures was associated with better proof performance. Thus, identifying individual factors and malleable environmental factors that elevated gesture production could lead to superior mathematical reasoning in an area that is vital for future educational advancement.

Teachers were more likely to produce any gestures and collaborative gesture sequences during proof activities when they were members of smaller groups. We also observed that teachers are more apt to produce collaborative gestures when those around them are gesturing. These social influences on gesture production signal potentially important and practical implications for teacher educators and designers' professional development interventions as they consider group size and group composition as factors directly under their control. Whether this plays out the same way for K-12 students is a subject for future research.

Teachers were also less likely to gesture during proofs when they believed gestures to be distracting. Given that gestures help with performance, the suggestion that negative attitudes toward gestures may show up in teacher behaviors may provide valuable diagnostic information that can inform future interventions targeted at teachers' belief systems. Believing that gestures are effective for learning also was negatively associated with overall gesture production, a finding that went in an unexpected direction. However, we also found that these same attitudes about gestures were *positively* associated with collaborative gesture production. This second finding may be more consequential because it is *collaborative gesture* that is ultimately predictive of proof performance among these teachers. While this invites further study, it points to the value of documenting gesture attitudes and the possibility that interventions targeted at gesture attitudes could positively influence mathematics reasoning, mediated, perhaps, by the collective gesture behaviors of one's collaborators.

The discussion here suggests several potentially fruitful directions for future work. First, proof production and geometric learning for smaller versus larger collaborative groups could be experimentally varied, with individual gestural tendency as a mediator. It would further be interesting to simultaneously examine how participation in the group's reasoning via talk moves changes as groups become smaller or larger. It may be that participation structures for gesture production are quite different than those for speech.

Second, future studies could test whether purposefully placing low-gesturers in groups with high-gesturers might increase low-gesturers' collaborative gestural production and increase their proof performance. Social and dispositional factors have been identified as important for determining the threshold for a speaker's resistance to overtly producing a gesture (Hostetter & Alibali, 2019), but little research has specifically examined how to increase the tendency to gesture as a way to increase learning and understanding. Creating a social situation where learners feel comfortable gesturing and feel like their contributions will be meaningful, and thus have lower gesture thresholds, may be key to promoting math learning for each individual participating in a group dynamic.

Third, interventions where group members are all explicitly encouraged to make collaborative gestures could be tested to see if they improve problem-solving outcomes. In the present study, we told the students they could not use writing implements and that their hands should be empty, but other more direct approaches could be used to encourage gesture. We can also explore how positive effects from collaborative gesture may carry forward and show a gestural trace in mathematical reasoning outside of the collaborative setting.

An interesting avenue for future research would be interventions that attempt to change people's beliefs about gesture—like those indicated on the TAGLI survey—and then examine how changing those beliefs impacts gesture usage and problem-solving. Many teachers may not be aware of the importance of gesturing or may not think gesturing or paying attention to student gestures is a particularly important element for them to be focusing on. Interventions that seek to increase gesture usage may not be successful unless they take into account underlying beliefs about teaching and learning.

Our chapter paints an optimistic picture of how understanding attitudes and social considerations influence gesture production and performance on advanced areas of mathematical thinking (see Megowan-Romanowicz et al., chapter 11 in this volume; Tancredi et al., chapter 13 in this volume). This invites new opportunities for embodied educational innovation as well as new areas of research on the embodied nature of teaching and learning.

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Note

1. For regression tables and additional descriptive information, please contact the authors of this chapter.

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10

Manipulatives and Mathematics Learning: The Roles of Perceptual and Interactive Features

Andrea Marquardt Donovan and Martha W. Alibali

Imagine a child working with a balance scale as they are learning about the concept of equality. They look at a symbolic equation and count out blocks to represent the numerical values on each side of the equation. They then place the blocks into the pans on either side of the balance scale and look to see whether the scale balances. Does the presence of the blocks and the balance scale influence the child's understanding of the concept of equality? Do the physical and interactive features of the blocks and the balance scale invite certain actions, which in turn lead to better (or worse) understanding?

A wealth of research has investigated the effects of concrete manipulatives on student performance, learning, and achievement. Several studies have revealed benefits of using concrete objects in a range of tasks. For example, Carraher et al. (1985) found that children were more successful in solving arithmetic problems with real-world objects than solving comparable, symbolically presented problems. They argued that the objects activated real-world knowledge, leading to more accurate performance. Glenberg et al. (2004) found improved reading comprehension and memory when children modeled story actions using physical objects. Indeed, a recent meta-analysis found an overall positive effect of manipulatives on student learning outcomes (Carbonneau et al., 2013). Teachers also endorse the benefits of manipulatives: Moyer (2001) found that teachers believed that learners were more motivated when students used manipulatives, and Moch (2001) found that students expressed positive perceptions about mathematics when they used manipulatives.

By contrast, several studies have revealed challenges or inconsistent benefits of using manipulatives. For example, Donovan et al. (2016) compared students learning to solve mathematical equivalence problems (e.g., $3+4=5+\_\_$) in lessons that used three different types of manipulatives and in a control condition that involved symbolic problems only. There were no benefits of using manipulatives for problem-solving performance, though there were benefits for conceptual understanding of equality. Furthermore, small differences in the features of manipulatives can moderate their effects (Petersen & McNeil, 2013). Finally, the effects of manipulatives also vary depending on characteristics of the instruction and on methodological features of the research (Carbonneau et al., 2013).

These mixed findings have sparked much debate, both among researchers and among teachers. Indeed, middle school teachers sometimes report viewing manipulatives as "fun" but as not reflecting "real math" (Moyer, 2001).

In this chapter, we review research on how perceptual and interactive features of manipulatives afford actions and on how those actions connect to target concepts. We acknowledge there are many other factors that may influence the effectiveness of manipulatives, including features of the instruction (e.g., Carbonneau & Marley 2015), children's prior experience with the manipulatives (e.g., Mayer, 2003), and the ways in which the manipulatives are introduced (Donovan & Alibali, 2021). In this chapter, we focus on characteristics of the manipulatives themselves, specifically the perceptual and interactive features of manipulatives and the *affordances,* or possibilities for action, they offer. We argue that considering manipulatives in terms of affordances can provide new insights into the varying effectiveness of manipulatives in different contexts. We close by discussing implications for the design of lessons that use manipulatives for math instruction.

For the purpose of this chapter, the term "manipulatives" refers to physical objects that can be touched and moved with the hands during problem solving and learning. Some example manipulatives include blocks, chips, Dienes blocks, Geotiles, balance scales, paper clips, popsicle sticks, and beanbags. A growing body of work focuses on computer-based, virtual manipulatives (Moyer-Packenham & Westenskow, 2013; Stull et al., 2013; Suh & Moyer, 2007), which hold promise because technology offers unique affordances for action. However, in this chapter, we focus on manipulatives as objects that can be physically manipulated with the hands.

Manipulatives vary along many dimensions, and some of these variations have implications for how learners perceive and interact with the manipulatives. In the following sections, we consider the perceptual and interactive features of manipulatives in turn.

Perceptual Features of Manipulatives

Perceptual features of manipulatives include features such as color, shape, pattern, visual complexity, degree of perceptual detail, and so on (Willingham, 2017). Objects used as manipulatives vary in their perceptual richness, with some objects being perceptually bland with simple shapes and plain colors, and other objects being perceptually rich with bright colors, unique shapes, and a high degree of perceptual detail. For example, two types of manipulatives that are currently marketed to teachers as useful for counting tasks include simple, bland chips and rich, detailed “bug counters,” which are multicolored plastic bugs (grasshoppers, beetles, dragonflies, etc.) thought to “capture students’ interest in counting activities” (Learning Resources 2021). Both can be used for counting, but is one more effective than the other?

The perceptual characteristics of manipulatives may influence the ways that learners engage with the manipulatives. Perceptually rich manipulatives may engage learners and stimulate exploration because they draw attention with bold colors, interesting shapes, or compelling details. Some support for this idea was found by Petersen and McNeil (2013) in research on preschool children’s counting performance. When the objects to be counted were unfamiliar, children displayed better performance with perceptually rich objects than with perceptually bland ones. For familiar objects (such as toy animals), however, perceptual richness actually hindered children’s performance. Other studies have also suggested that perceptually rich manipulatives are more likely to elicit irrelevant or off-task behavior (e.g., Uttal et al., 2013). Perceptual details may be distracting for learners, and they may evoke or activate knowledge that is irrelevant to the task at hand.

Maria Montessori (1964), one of the first women to put the education of children into the public eye, would not be the least bit surprised. During her quest to establish an educational environment in the tenements of Rome, she expressed a very different intuition from many educators. Montessori believed that didactic materials should be made from the most natural of substances available, and that careful thought should be given to each object being placed into the children’s learning environment. Montessori believed that each feature of any learning material in the classroom should have a specific purpose and should have no extraneous purpose, so as not to distract from the connection between the material and the concept. In her view, learning materials should be designed for learning and not for visual pleasure.

In line with Montessori’s intuition, several studies have demonstrated that perceptually bland manipulatives enhance performance, relative to perceptually rich ones. For example, McNeil et al. (2009) investigated the effects of perceptually rich and bland manipulatives on children’s abilities to solve story problems about money. They found that students who used perceptually bland coins and bills performed better on the story problems than those who used perceptually rich materials that looked like “real” money. However, they also found that the errors children made in the perceptually rich condition were less likely to be conceptual errors that reflected fundamental misunderstandings of the problems.

Another study that revealed differential benefits for rich and bland manipulatives focused on preschoolers' understanding of numerical inequalities using objects as counters (Carbonneau & Marley, 2015). In this study, the realistic manipulatives were green toy frogs, and the bland manipulatives were simple green circles. Although the type of manipulatives used did not influence participants' abilities to apply procedures to solve the problems, participants who used rich manipulatives displayed less knowledge about the underlying structure of the problems than those who used the bland manipulatives. Participants who used rich manipulatives, however, outperformed those who used bland manipulatives on transfer items, which involved comparing quantities using a number line. The different findings for performance and transfer suggest that rich and bland manipulatives may support different aspects of children's learning.

Manipulatives with different perceptual features may influence learning in different ways. The mixed findings in the literature suggest that the goals of lessons need to be carefully considered and that manipulatives should be selected based on those goals. For example, if the goal of a lesson involving money is to build arithmetic skills, then perceptually bland materials might be the best choice. If the goal is to promote foundational understanding of currency and change making, then perceptually rich bills and coins might be the better choice. To our knowledge, guiding principles for choosing manipulatives to suit differing educational objectives have not yet been explored. Considering this distinction in future research on manipulatives could lend clarity to the debate.

Interacting with Manipulatives

Perceptual characteristics of manipulatives may be important, not in and of themselves, but because of the differing actions that they invite. So rather than making a blanket statement that perceptually rich or bland manipulatives are a "better" choice for student learning, a reframing of the question may be needed. What sorts of actions do specific manipulatives afford? James Gibson (1979) argued that *affordances* are the inherent qualities of an environment that allow particular actions on the part of a particular organism within that environment:

> The affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or ill. The verb *to afford* is found in the dictionary, the noun *affordance* is not. I have made it up. I mean by it something that refers to both the environment and the animal in a way that no existing term does. It implies the complementarity of the animal and the environment. (p. 127)

In the Carbonneau and Marley (2015) study, the green frogs may have had *affordances* that that green chips did not. The green frogs may have afforded actions such as making the frogs "jump" or holding a single frog in one's hand. The chips, by contrast, may have afforded stacking or holding many in one's hand at once. Did these differing affordances prompt children to perform different actions that may have helped or hindered their performance on the experimental tasks? Or did the green frogs and chips each relate to the concepts being taught—underpinnings of mathematical equality and inequality—in different ways?

In fact, in all of the studies reviewed thus far, different materials afforded differing actions—different ways of interacting with the manipulatives. We use the term *interactive features* to refer to features of manipulatives that may influence how learners interact with them, such as their size, weight, and their ability to be picked up and handled. Learners' history of actions on the objects and the conventional ways in which the objects are handled or used may matter as well. For example, it may be challenging for learners to use a toothbrush as a measuring device because the usual way in which a toothbrush is used—for brushing teeth—is both conventional and well-practiced. Rather than making general claims that some manipulatives are better or worse for student learning, we must consider the interactive features that particular manipulatives have and the actions those features afford.

Manipulatives with different degrees of perceptual richness may also have different interactive features. Rich perceptual features may invite learners to explore the objects manually in the first place. Realistic manipulatives (such as the toy frogs) may invite learners to interact with the objects in ways that are shaped by learners' prior knowledge and experience with the objects (in this example, the toy frogs) or the things they represent (in this example, real frogs).

At the same time, realistic features may be detrimental to learning with manipulatives because real objects afford specific actions that may not be relevant to the target concept. For example, crayons may not be well suited to being counters because they invite drawing rather than being counted. By contrast, bland manipulatives may allow children to look beyond their knowledge of the objects themselves and to act on the objects in ways that relate to the concept being taught. Pouw et al. (2014) argue that perceptual features invite particular actions on manipulatives, thus "embedding" learners' cognitive activities in the objects. In this sense, the varying perceptual features of manipulatives and the actions they afford may lead to differing experiences with manipulatives—a two-way flow between the features of the manipulatives and the actions of the learner.

How Perceptual and Interactive Features Support Learning with Manipulatives

When people see objects, they automatically activate plans for actions that they could perform on or with those objects. Neuropsychological evidence suggests that when people view objects with strong associations to possible actions, such as tools, they experience activation of premotor and motor areas (e.g., Grafton et al., 1997). Moreover, people experience greater motor activation when viewing objects that are readily manipulated (such as an apple) than when viewing objects that are not easily manipulated (such as a traffic light) (e.g., Gerlach et al., 2002). These findings suggest that when people see particular objects, they perceive affordances for actions on those objects.

This general principle can be applied to manipulatives, as well. Affordances for action may be set in motion when the manipulatives are perceived or may be activated when the manipulatives are handled. The affordances of the manipulatives may invite or constrain particular sorts of actions and explorations. Different manipulatives may prompt differing actions, such as touching, grasping, rotating, stacking, pushing, lifting, and so forth. When learners lack relevant knowledge, strategies, or teacher guidance to inform their actions, the affordances of the manipulatives themselves can inform their actions (Manches & O'Malley, 2016).

Manipulatives that afford actions that closely align with the concept being taught could contribute to student success. In some cases, merely touching the manipulatives may be enough to boost performance, as in preschool children's counting (Alibali & DiRusso, 1999). In this case, the target concept of counting was closely tied to sequential touching, and sequential touching enhanced children's counting performance.

Other research on action and cognition suggests that when learners produce actions that align well with the target concepts, they make greater progress than if they make irrelevant or conflicting actions (e.g., Nathan et al., 2014; Thomas & Lleras, 2009). This same principle may hold for actions with manipulatives, as well. Depending on how closely the actions with the manipulatives align with concept being taught, learners may have a more or less aligned physical experience of the concept.

One recent study compared students' learning from varying manipulatives that afforded different sorts of actions. Donovan, Alibali and Waters (2016) taught elementary school students the concept of mathematical equivalence with three different types of manipulatives, each of which afforded different sorts of actions. One group received a lesson and practice with a balance scale, another group received a lesson and practice with Lego blocks, and another group received a lesson and practice with a set of buckets and beanbags. Each of the manipulatives was intended to support students in understanding equivalence, but each afforded very different actions. In the pan balance group, students used their dominant hand to place the cubes into the pans, and they relied on visual cues to support the connection between the pan balance and the equation. In the Lego blocks group, children used both hands to stack the blocks into two towers that represented the values on the two sides of the equation. In this condition, children also relied on visual cues to support the connection between the heights of the Lego towers and the values on each side of the equation. In the buckets and beanbags group, students engaged both hands as they "became" the balance scale with their bodies, by picking up the buckets with both hands and holding them out to their sides with the beanbags placed in them. Thus, each of the three manipulatives afforded very different actions.

Donovan et al. found that some forms of action were more helpful than other forms for fostering conceptual understanding of equivalence. Many children in the bucket-and-beanbags condition and the blocks condition demonstrated a relational understanding of the equal sign at posttest, but very few of the children in the pan-balance and control conditions did so. In the buckets-and-beanbags condition, children simulated a balance scale with their own bodies; that is, they used their bodies to physically experience or "feel" the concept of equivalence by holding the buckets and beanbags of equal weight in their two hands. The buckets and beanbags afforded actions that the other materials did not—specifically, being lifted with two hands by the child. By "becoming" the balance scale themselves, the children felt the identical weights of the buckets and performed the same action with both hands—both experiences that highlighted the idea of *sameness,* which is central to the concept of mathematical equivalence. In the blocks condition, children created two block towers and then engaged in visual comparison of quantities by looking back and forth between the two towers. Both in construction and in visual comparison, the *sameness* of the towers' heights was highly salient. By engaging the body in actions that were readily aligned with the very concept to be learned, children could take advantage of additional sensory and perceptual input that was not available in the other conditions.

Martin (2009) has suggested that when a learner is "stuck" on an idea, action might also help spark a new idea. According to this account, actions can help learners develop new interpretations of concepts. When representing equations with buckets and beanbags, the action of lifting a bucket in each hand and the experience of feeling the same amount of weight in each hand may have helped learners to develop a new interpretation of equality. Indeed, one of the participants in the buckets-and-beanbags condition continued to talk about the buckets and beanbags on the posttest, when they were no longer available for use (Donovan et al., 2016). For example, in trying to solve the symbolically presented problem $5+7=4+\_\_$, the child said, "Can I just pretend I have the bucket? Because, um, the bucket I'm pretending to have, has . . . four beanbags in one and five in the other. I added one more to the, um, other, the four one, that would equal five . . ."

Other research also supports the view that actions on manipulatives can make learners more open to new ways of thinking about concepts. In one study that focused on understanding of fraction division (Sidney & Alibali, 2017), fifth- and sixth-grade students were asked to represent a series of arithmetic expressions with whole numbers and fractions using plastic fraction bars. Each individual bar represented one whole, but the bars could be broken into different numbers of fractional pieces; for example, some of the bars could be split into two pieces to represent halves, others could be split into three pieces to represent thirds, and so on. To model $12 \div 3$ (a whole number division expression), a child might place 12 bars on the table and then divide them into three groups of four bars each. Similarly, to model $12 \div 1/3$ (a fraction division expression), a child might place twelve bars on the table and then divide each bar into thirds, yielding thirty-six pieces.

The primary focus of the study was on participants' abilities to successfully model fraction division, and specifically on whether particular sequences of items differentially supported them in doing so. Participants who modeled *whole number division* just prior to fraction division were more successful than participants who modeled *fraction multiplication* prior to fraction division—presumably because the relevant actions were well aligned for whole number division and fraction division. These findings suggest that the action of representing whole number division as "forming groups of a particular size" supported learners in conceptualizing fraction division as "forming groups of a particular (fractional) size." Thus, participants' actions with the manipulatives appear to have influenced their understanding of the target concept of fraction division.

Depending on the actions afforded by particular manipulatives, children may engage with manipulatives in ways that spark new ideas or that make them open to thinking about concepts in new ways. Thus, by inviting particular actions, manipulatives may aid learners in exploring conceptual spaces in fruitful ways.

Connecting Manipulatives to Concepts

The focus of this chapter thus far has been on how perceptual and interactive features of objects afford actions. It is also critical, however, to consider how both objects and actions relate to concepts. For manipulatives to be effective, learners need to be able to map from the concept to the manipulatives, from the manipulatives to the action, and from their actions on the manipulatives back to the target concept. The ease with which learners can make these mappings is sometimes referred to as the *transparency* of the mappings. Is the target concept “obvious” in the object itself? Is it highlighted in the actions afforded by the objects? Are the actions that are afforded by the objects the important ones for learning the concept? Researchers have distinguished two contributors to transparency: (1) the mapping from the physical object itself to the concept (which is sometimes referred to as *epistemic fidelity*; see Roschelle, 1994), and (2) the mapping from action to the concept.

One key to understanding transparency may be exploring what makes individuals believe two things are the “same.” Some similarity relations may seem natural or obvious, in the sense that there is an easily apprehended connection from the object or action to the target concept. For example, there is a natural, easily apprehended connection between the action of sequential touching and the concept of counting. Other similarity relations may require instructional support that highlights corresponding features of the object or action and the target concept, using common labels or gestures, spatial alignment, or making explicit mappings, such as instructional analogies. The need for such supports may be greater if the connections are less transparent.

We argue that, in order for manipulatives to be beneficial for learning, the connections from the manipulatives and/or the actions performed to the target concept need to either be transparent or be supported via instruction. Considering these connections may help educators choose what manipulatives to use and how to instruct learners in using them. Thus, we argue that, in deciding whether and how to use a given manipulative, educators need to first identify the target concept, then (1) consider the goals of the lesson; (2) consider how the manipulatives under consideration relate to the target concept; (3) consider what actions the manipulatives afford; and (4) consider how those actions relate to the target concept.

Manipulatives to Concept

To enhance the likelihood that manipulatives are beneficial, they should physically align with the target concepts to the greatest extent possible. One construct that has been invoked to capture this alignment is the idea of *epistemic fidelity* (e.g., Meira, 1998; Roschelle, 1990; Wenger, 1987). Epistemic fidelity can be defined as “the strength and breadth of the analogical mapping of the physical material to the [mathematical] domain” (Stacey et al., 2001, p. 200).

Representations that have high epistemic fidelity are easily mapped to the target domain because the analogical mappings are strong and deep. If the mapping from the manipulatives to the concept is perfectly transparent, learners should be readily able to use the manipulatives to build their understanding. For example, in their study of reading comprehension, Glenberg and colleagues (2004) found that children who manipulated objects that physically resembled the people and objects described in a story performed better than children who simply reread the story. The manipulatives that the children used mapped transparently to the characters and objects in the story, so the links from the manipulatives to the target concepts were easily apprehended by the learners. If the connection from the manipulatives to the concept is less transparent, then learners may not benefit from the manipulatives as intended. For example, if the objects in the study by Glenberg and colleagues had not looked like the characters and objects in the story—that is, if they had looked like other characters and objects—participants might not have performed as well.

Kamii et al. (2001) made a related argument to support their view that a balance scale is *not* a useful manipulative for teaching children about addition. They argued that addition is a mental operation in which two values are combined to make a higher-order value. Importantly, the two original values remain part of the larger value; for example, in $3+2=5$, the 3 and the 2 remain "in" the 5. This part/whole structure is not reflected in the balance scale, where one side might be used to represent $3+2$ and the other side to represent 5. In this respect, the balance scale does *not* have epistemic fidelity with the operation of addition. In the view of Kamii and colleagues, mathematical relationships are not well represented by the physical phenomenon of balancing sides, so they recommend against the balance scale as a tool for teaching arithmetic.

As another example, Stacey et al. (2001) compared two different materials for teaching decimals—one that they deemed to have greater epistemic fidelity and one that they deemed to have less epistemic fidelity. Specifically, they compared learners' understanding of decimal concepts after lessons that involved linear arithmetic blocks, which represent quantity in terms of *length,* or multibase arithmetic blocks, which represent quantity in terms of *volume.* Stacey and colleagues argued that length connects more transparently to number than volume. Indeed, they found that the linear arithmetic blocks promoted greater learning of the target decimal concepts than the multibase arithmetic blocks, as well as more active engagement and deeper discussion of the concepts.

Stacey and colleagues were quick to point out that the effectiveness of manipulatives cannot be predicted by epistemic fidelity alone, because the two types of blocks also differed in other ways. Though different learning materials can have varying levels of epistemic fidelity, it is also possible that transparency is made by the learner from their actions (Meira, 1998). From this perspective, transparency may derive not only from features of the object itself, but also from the process of acting on or using that object.

Actions to Concept

Some particular actions may align with a target concept more or less than other actions. In some cases, the structure of objects makes certain actions on those objects natural or obvious. Gaver (1991) called these natural affordances "perceptible," meaning that they offer a direct link between the object and the action. If an object naturally affords particular actions, and if these actions are well aligned with the target concepts, learning may be enhanced.

Returning to the study of reading comprehension described earlier, Glenberg and colleagues (2004) asked children to physically act out the story with objects. In this case, the objects naturally afforded certain actions, and these actions aligned well with events in the story itself, so the actions enhanced comprehension of the story. Likewise, in the study of mathematical equivalence described earlier (Donovan et al., 2016), the buckets naturally afforded participants placing beanbags inside them and lifting them by their handles. Lifting the buckets allowed participants to feel the weights of the buckets and to experience whether they were the same. The actions with the buckets supported understanding of mathematical equivalence because these actions aligned readily with the target concept of equivalence.

As with the link from manipulatives to the concept, if the "reach" from the action to the concept is too far, the relation between the two may not be apparent to the learner, and the learner may not benefit from acting on the manipulatives. In the study of mathematical equivalence described earlier (Donovan et al., 2016), children who placed cubes on a pan balance did not demonstrate substantial gains in understanding of mathematical equivalence. The action of placing cubes in pans may have been challenging to align with the target concept.

Just having manipulatives present is not enough to evoke actions that align with the concept being learned—and indeed, relevant actions may need to be modeled for the learner. Again, the buckets and beanbags provide a valuable example. In addition to placing and lifting actions, these objects also afford tossing the beanbags into the buckets—and many children choose to engage in such actions when they encounter these materials. Tossing actions do not ordinarily align well with the concept of mathematical equivalence, but depending on how the beanbags are tossed, they may not enhance learning of equivalence, but they may not harm learning of the concept either (see Donovan & Alibali, 2021).

In sum, to ensure that the manipulatives are beneficial, the manipulatives themselves should physically align with the target concepts, and the actions performed on those manipulatives should also physically align with the target concepts. If the object features and relevant actions are not readily connected to the target concepts, support for these mappings may be necessary to increase the likelihood of successful learning.

Implications for the Design of Lessons Using Manipulatives: Promoting Understanding of Relevant Connections

With so many differing types of manipulatives available to teachers, choosing which ones to use and how to use them can be a daunting task. Given the conflicting findings about the effectiveness of manipulatives (e.g., Carbonneau et al., 2013), caution should be used in deciding how and under what circumstances they should be used. We have argued that it is crucial to consider whether learners can appreciate the connections from the manipulatives to the concept to be learned, as well as the connections from the actions afforded by the manipulatives to the concept to be learned.

There may be an optimal structure for manipulatives to be beneficial to learning. We suggest that the most effective manipulatives are objects that offer transparent links to the target concepts and that afford actions that readily align with the target concepts, as well. In our view, transparency can emerge either as a result of the perceptual features of the objects themselves or as a result of their affordances for action. Thus, the best manipulatives are those that can be readily linked to the target concepts based on their perceptual and interactive features.

Conclusion

In this chapter, we have considered perceptual and interactive features of manipulatives and how these features contribute to or detract from student learning. We considered the varying *affordances* for actions that manipulatives possess, and we highlighted the varying ways in which physical objects and actions connect to target concepts. These considerations from perception and action can help to describe, explain, and predict why certain types of manipulatives are more or less effective for learning. Finally, we considered the issue of the transparency of the connections between manipulatives and the concepts to be learned, both in terms of the objects themselves and in terms of the actions afforded by the objects.

An embodied perspective on cognition holds that "cognitive processes are rooted in the actions of the human body in the physical world" (Alibali & Nathan, 2018, p. 75). From this perspective, the body and the motor system are integral to psychological processes (Glenberg, 2010). It may be the case that physical activity in general opens the mind to new ideas, as some authors have suggested (e.g., Have et al., 2018). However, in this chapter, we have argued that manipulatives and the actions they afford can also be a driving force behind changes in thinking.

Indeed, many researchers as well as practitioners advocate that actions with manipulatives can support learners' construction of more advanced conceptual structures (e.g., Fuson et al., 1997). However, the beneficial effects of manipulatives may only be realized over time and with careful planning. We have outlined several considerations that are paramount for deciding whether and how to use a given manipulative: identifying the target concept, considering how the object under consideration relates to the target concept, considering what actions the object affords, and considering how those actions relate to the target concept.

We have argued that an affordances perspective can provide new insights into the body of conflicting findings about the effectiveness of manipulatives. To understand the dynamic processes of learning with manipulatives, a new framework is needed—one that places manipulatives' *perceptual and interactive features* at the center. These features highlight the importance of learners' *actions on manipulatives* and at the same time emphasize the necessity of transparent *connections* to the target concepts—both connections that seem natural and obvious, and ones that can be made with instructional support.

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11

Physics and Gesture: Spatial Thinking and Mutual Manifestness

Colleen Megowan-Romanowicz

Introduction

Schooling has been a primarily face-to-face activity for millennia, but in early 2020 the world changed. With the arrival of the COVID-19 pandemic, education nearly worldwide was quickly shifted to a distance learning transaction (UNESCO Global Education Coalition, 2020). What will this shift cost teachers and students with respect to their ability to effectively communicate, to make their thinking "mutually manifest" (Wilson & Sperber, 2006)?

Although it is true that "schooling" and "learning" are often conflated (Gobby & Millei, 2017; Illich, 1971), there is ample evidence that better learning happens when socially situated in authentic activities (Anderson, et al., 1996; Brown, et al., 1989; Dewey, 1923). When students work collaboratively within their classroom "community of practice" to collectively make sense of phenomena (Lave & Wenger, 1991; Putnam & Borko, 2000; Vygotsky, 2012), their thinking and cognitive development are influenced positively by the social context (Rogoff & Lave, 1984).

The study of physics engages students with fundamental models of space and time, forces and motion, and matter and energy. When people talk about such abstractions they invariably supplement words with the language of gesture (Kendon, 2000)—representational gestures that depict action, motion, trajectory, shape, or location. Gestures have been shown to contribute significantly to effective communicating spatial information (Alibali, 2005).

Gestures are an integral part of making one's thinking "mutually manifest," that is, communicating one's mental model to another in such a way that the "other" knows it and is able to work with it just as the "one" does. For example, we can think of Mr. Spock and the Vulcan mind meld on the TV series *Star Trek* (Covington, 1998). The tight linkage between cognition and sensorimotor systems is well documented (Barsalou, 2003; Beilock, 2009; Lakoff, 2003).

Theories of embodied cognition point to the fact that thinking, interacting with surroundings, and communicating are fundamentally shaped by the body's location in space and time. Moreover, there appears to be a feedback loop among thinking, speech, and gesture—not only do our thinking and speaking shape our actions or *gestures,* our actions or *gestures* shape and assist our thinking and speaking (Goldin-Meadow, 1999; Kita et al., 2017). This is the gesture-for-conceptualization hypothesis.

An embodiment framework proposes that knowledge is highly dependent on sensorimotor activity, such that learners physiologically feel forces and exert agency over those forces during a lesson. Learning is primed by what we perceive, and what we expect in the world as we move about it, in addition to how we interact with the objects and situations discovered (see Johnson-Glenberg et al., 2016, p. 3). Knowledge is *in* the perceptual interpretations and motoric interactions (Goldstone & Wilensky, 2008, emphasis added). Gestures and full-body movements, when integrated into large digitized science lessons, foster more positive attitudes toward science (Lindgren et al., 2016).

Teachers rely heavily on gestural information to assess the conceptual coherence of student thinking in the learning environment (Alibali et al., 1997; Fargier et al., 2012). On-the-fly, formative assessment based on both verbal and nonverbal cues is a well-documented teaching strategy (Li, et al., 2018; Shavelson, et al., 2008). In a physics classroom where students work to make sense of real-world phenomena, their communicative interactions with their classmates routinely encode spatial and temporal information in both speech and gesture (Johnson-Glenberg & Megowan-Romanowicz, 2017; Scherr, 2008).

Ideal virtual learning environments can support socially situated learning to some extent (Coronado-Hernandez, et al., 2016). In the best of cases, virtual learners are equipped with fast internet access and mobile devices capable of two-way communication via videoconferencing software (de Oliveira Dias et al., 2020).

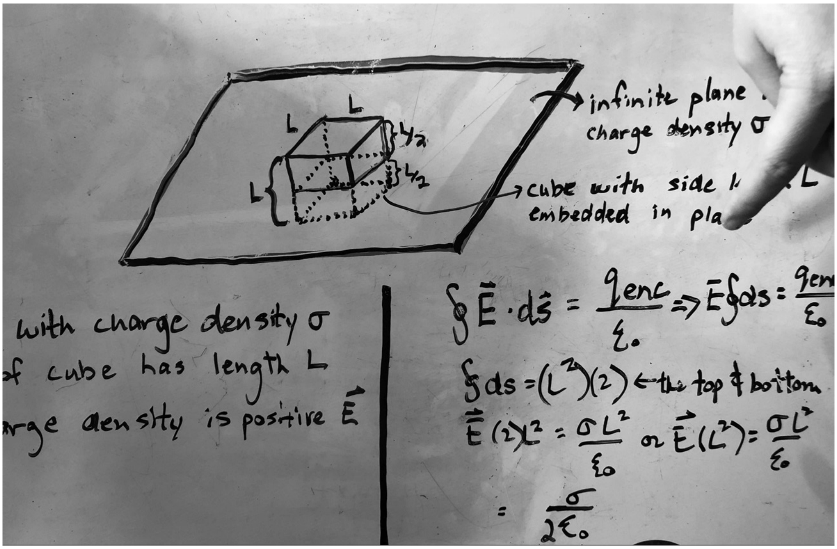
Access at home to virtual courses taught in an ideal (e.g., interactive in real time) learning environment is not necessarily the norm for many students, particularly students of color and students living in low-income households (Auxier & Anderson, 2020). This chapter contrasts an episode of face-to-face physics learning with this best-case virtual scenario—physics taught via interactive videoconferencing.

Little is known about how teaching and learning will be impacted when gestural and postural information is no longer readily accessible. There has been some investigation of the role of facial expression and posture in video learning (Shan et al., 2007), but nothing yet about discipline-specific learning undertaken via Zoom, Google Meet, or the like.

Making Sense of Electric Fields: A Snapshot of Thinking and Learning Physics

The following vignette illustrates a typical day in a physics classroom before the COVID-19 pandemic. Imagine as you read how this same class might look conducted as a video lesson on Zoom.

> Echo Mountain Community College is a medium-sized two-year college on the outskirts of a large city in the southwestern United States. A little over half the students enrolled there are women, 31 percent are Hispanic, and 47 percent are White. The following episode occurred in a second semester physics course on electricity and magnetism. The learning environment is not unlike that in a high school advanced placement or honors physics course.
>
> The teacher, Dave Donnelly, is in his early thirties. He earned his PhD in physics education research at a large state university. It is early October, and they are about a third of the way through the course.
>
> The classroom is a large square room with laboratory tables jutting out from three walls at the sides and back of the room and a large open area of about twenty feet square in the midst of these tables.
>
> Each table seats four students comfortably. Students begin to write or sketch on 60 × 80 centimeter whiteboards as their groupmates arrive for class, working together to represent a homework problem they had been assigned over the weekend: describe the electric field on a cube or cylinder that is embedded in an infinite plane of charge density σ.
>
> The teacher, clad in shorts and sneakers and looking a great deal like a student, strolls around the room peering at the boards the students are preparing. As Donnelly completes his circuit of the classroom he intones, "All right, ladies and gentlemen, bring yourselves on in."
>
> Students scoot their rolling chairs into a rough circle in the center of the classroom. Once everyone is settled, he gestures with an open hand to a girl with long blond hair, Kiki, saying, "Thank you. Nice and loud."
>
> She looks down at her group's board and then begins, tracing the figure on her diagram as she speaks: "We chose a cube because that way the electrical field could be . . . like . . . equal . . . so . . . because it's constant. It comes out of the plane at a right angle." She gestures with her hands at right angles to one another.
>
> She begins pointing out certain features on her diagram, a picture of a cube embedded in a plane with sides perpendicular to the plane (see figure 11.1): "We drew the cube with sides of length *l*, and all these four sides [touching the four sides embedded in the plane], and the electrical field lines are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∮E·ds = q_enc/ε₀ ⇒ E∮ds = q_en/ε₀
∮ds = (L²)(2) ← the top & bottom
E(2)L² = σL²/ε₀ or E(L²) = σL²/ε₀
= σ/2ε₀

Figure 11.1
Kiki's white board.

perpendicular to the direction of the surface [with one arm horizontal in front of her as if to indicate it was a plane, she places her other hand behind it pointing vertically], so the four sides don't really matter much."

She goes on to describe how they constructed their equation (pointing back and forth from diagram to equation as she describes each term): "Since the electrical field lines are constant we took that out of the integral, and the direction of the surface, since we weren't really counting the height or the distance from the infinite plane—we just kind of left that out." She proceeds to describe why they chose the values they substituted into their integral and explain that they multiplied by 2 to account for the top and the bottom of the surface.

She finishes her explanation pointing to each of the algebraic steps they took as she explains that the electric field, E is equal to $\sigma/2\varepsilon_o$.

"Makes sense," John ventures tentatively.

There is a pause. Kiki's classmates gaze in thoughtful silence at her board. Some write in their notebooks. Kiki points to another group's whiteboard, saying, "You guys got the same thing."

Finally, a burly, pony-tailed, pierced-eared young Hispanic man, Ruben, asks why it is that the distance between the plane and the cube doesn't matter. Kiki responds that regardless of what the distance is, the field lines will be perpendicular to the surface: "They cancel out." Gabe, a slight, bearded Hispanic man, says he had debated whether to use a cube or a cylinder and wondered if that would make a difference. Kiki responds that it would make no difference, as long as the sides of the cylinder are perpendicular to the plane. Gabe suggests (laying his left hand diagonally against his horizontal right arm) that if Kiki drew a diagonal from some point in the cube to one of its corners, “the length wouldn’t be l anymore.” Another voice from the group chimes in: “But the electric field lines are perpendicular to the plane.” After a little more discussion, Gabe finally capitulates.

As the talk subsides, Professor Donnelly (who has been sitting quietly outside the circle, watching and listening) looks to Kiki and asks, “All done?” She nods. “Everybody got it?” They look around at each other. “I see some quizzical looks. What about you, John?” Chin on hand, John stares at Kiki’s whiteboard intently.

“So does it matter how high above your infinite plane you are?” Donnelly asks, looking around at the group. A few heads shake.” A number of students are staring intently at their notebooks and make no response. He presses them, “Does this make sense to everybody? Have you ever seen a situation where no matter where you are [sweeps his arm around him], something is always the same?”

The conversation shifts to a discussion of the gravitational field. They come around to the question of whether it is reasonable to pretend something is infinite when it is not.

Students nod without hesitation—they all agree that it is.

Donnelly pounces: “When is it okay?” Silence. The students’ eyes slide from left to right looking to see if anyone will pipe up with a suggestion or a rule of thumb. Donnelly watches them intently for a few moments, scolds them gently, and asks the question again: “When is it okay to pretend that [pointing to the whiteboard that he has tossed on the floor in the center of the group] is an infinite plane?” He reminds them, “We often treat the earth as if it’s flat—is it really?” Heads shake. “No.”

“Well then, when is it okay to pretend that [points to the whiteboard] is an infinite plane?” Students begin brainstorming: “When you have to, to solve a problem?” “When it’s the whole universe?”

Donnelly is relentless.

“When can we consider that an infinite plane? What’s the definition of an infinite plane?”

There is some discussion about the thickness of the plane. He brings them back to the essential question: “So when’s it okay to consider that an infinite plane?” The students are out of ideas. They look around at each other uncomfortably, and eventually they look at him, waiting.

Donnelly picks up a marker, holds it at arm's length above his head, and asks if they could use the electric field equation that they have to calculate the field this high above the whiteboard. Several students shake their heads. "How about here?" He drops the marker down to within a couple of centimeters of/ the surface of the board. Gabe quickly responds, "Yes!"

"Why?"

"Because the distance is small, relative to the size of the plane," Gabe replies.

Donnelly looks around. "Does everybody understand what he's saying?" Gabe holds a marker a few centimeters above the whiteboard; with the thumb and forefinger of his other hand, he measures the small interval of space between the whiteboard and the marker. Donnelly asks the group what they think. The silence stretches out as they look back at him. After a lengthy pause he says to them, "Don't look at me. I've asked the question ten times, and nobody's given me an answer yet: It's a start. I'm not saying you're wrong, I'm just saying what do the other thirteen of you think?"

A tall, bespectacled, dark-haired man, Rob, nods his head slowly, and he says, "That follows my train of thought. It's close enough that the distance to the edges is so significantly far that we can . . . that it doesn't matter how big it is. We can consider it infinity because it doesn't matter . . ." His voice trails off as he gestures with his hands moving wider and wider apart, to indicate that the diameter is getting larger: "Because it just goes so far that we don't need to consider how big it is." Students around the circle begin to nod their heads.

Kiki proposes, "When your distance in a straight line to the surface is less than your distance to the edge?" There is a long pause. A few students write in their notebooks; others stare at the whiteboard on the floor between them. Donnelly asks John what he thinks again, and John responds that he is still a little confused.

"What are you confused about?" Donnelly asks him. John replies that he doesn't see why the distance shouldn't matter. Bill, who sits across from him, agrees: "Yeah. Remember when we used that software that showed the electric field?" All eyes turn to the teacher looking for some sign that they were on the right track. He smiles as he leaves the group and turns to walk back and sit down at his desk: "I don't know. I'm going to let you guys answer that. Go ahead," he waves toward Gabe who proposed the idea originally.

Ruben jumps in, pointing to the equation. "This is different from what they did on the computer simulation because it's an infinite plane," he says, spreading his arms out wide. Then, pointing toward the equation on the whiteboard, he says, "No matter what it seems like, if the distance of an object from the plane does not appear in the equation then it must not matter." His last three words are accompanied with three decisive taps on the equation itself. At this point, several students talk about the counterintuitive nature of the situation. Kiki brings up the differences between how the field lines would look to a point in space above the plane if it was infinite (she hovers her head about sixty centimeters above the whiteboard and looks down at it with her arms stretched out wide) versus how that would be different if it was bounded (she draws her arms back toward the edges of the board, which is only eighty centimeters wide). The students seem to be coming around to Gabe and Ruben's view. Kiki finally turns to the teacher and asks, "What was the question again?"

Donnelly has been sitting at his desk, ostensibly looking at his computer screen but actually monitoring the exchange closely. "The question was, When can you consider that whiteboard to be an infinite plane? And John said that he didn't get it, so I left you all to get John's question answered. Did you get an answer?"

After a pause John utters in a monotone, "Yes." Donnelly prompts Ruben to repeat aloud whatever he just had said under his breath. "When you're a certain distance, close enough that you consider it an infinite plane, but if you go past that distance you have to . . . the distance is too great to consider it a plane. Like a point that if you cross it you can't consider it an infinite plane, but if you're below that you can," says Ruben.

Donnelly pushes on Ruben's idea: "So give me an idea. Where would you say that is?"

Ruben hesitates. "Well, I don't know."

Donnelly continues, "I didn't ask you what you know—I want you to guess. Show me how high above it would be."

"I don't know. Probably really close," says Ruben. He leans in and hovers the marker in his hand a few centimeters off the board, saying, "If you go too high [he lifts marker to about a meter above the floor] you can't do it anymore, but down here [drops the marker back down] it would be okay."

Donnelly continues, "Does everybody follow that? So which is it? Where is this magical point? Does it exist? And the answer is . . . ?"

More discussion ensues about whether it would be a function of the desired precision of the answer. In the end, they conclude that there is not an exact point. It all depends on how accurate you need your answer to be.

"But why is that important?" Donnelly probes.

Donnelly orders everyone to their feet. They follow him out the door, down the corridor, and out to the edge of the four-lane highway that runs along the edge of campus. He directs their attention to the power lines over their heads: “Above you are four wires. Are they infinite?” Heads shake. “No? Which way are they closer to infinity in? North or south?”

“North,” says a student.

To the south about a quarter of a mile, the wires angle down into the ground. The students agree that if they wanted to use Gauss’s law to determine the electric field where they were standing it would be okay because they are close to the wires in relation to their overall length and they are nowhere near the end.

Back in the classroom, Donnelly says, “All right. I heard some conversations on the way out there. Why is it that it doesn’t depend on how far away we are from an infinite plane?”

“Because the density of the field lines is the same everywhere?” This is from Brad, a spiky-haired, bleached-blond man who has been silent thus far.

Donnelly presses, “The density of the field lines is the same everywhere because the electric field is . . . the . . .”

“Same everywhere,” volunteers an unidentified male voice.

Donnelly continues, “Same everywhere. All right? But as you get farther above the plane, you just can see a little farther out. Okay? How far is it to the end of the plane from this point if we’ve truly got an infinite plane here?”

“Infinite,” says a student. “Infinite. It doesn’t matter if I pick here, here, here . . .” Donnelly gestures at various heights above the board.

Brad interrupts, “Doesn’t the strength of the field change the farther you get out?”

Donnelly points at the equation with his foot. “The math says . . .”

“No.”

“Why is it hard for us to understand that? None of us have ever seen an infinite object.” Donnelly stretches his arms wide. “It’s hard for us to envision. An infinite object looks the same no matter how far you are above it.”

It finally “clicks” for Brad: “Ah . . . but that’s just for infinite objects. Okay.”

The In-person Learning Environment

The classroom episode recounted above reveals that communicating about invisible physical phenomena (e.g., electric fields) entails a considerable cognitive load (Paas et al., 2003; Sweller, 2011). To help manage this load, it is typical in many science classrooms for the teacher to have students prepare for a class discussion by working in small groups to represent their thinking on a whiteboard (Megowan-Romanowicz et al., 2017). Each group prepares a whiteboard with diagrammatic, graphical, and mathematical representations of the problem to use as a visual aid—a tool for sense-making and mutual manifestness (Megowan-Romanowicz, 2011, 2013, 2016)—during the class discussion that follows.

The whiteboards almost always contain spatial information (as in figure 11.1), but students also make spatially congruent gestures as they describe their reasoning for their classmates. As they are preparing their whiteboards in small groups, they are coming to a consensus model of the phenomenon under investigation, and they are *rehearsing,* in both words and gestures, the way they will communicate their mental model—make it *mutually manifest*—to their classmates *and* to themselves. They are processing their mental model *in* its visuospatial context(s) (Kita et al., 2017).

In this episode, both the teacher's and the students' gestures and habits were integral to the multiway communication that took place, and to choices the teacher made about the pacing and direction of the lesson. Not only did students convey their physics thinking but also their confidence in their thinking and the (spatial) consequences of the equations they had derived.

Nuanced spatial information was encoded in both teacher's and students' gestures throughout the episode. By taking turns, the students' gestures referred to information encoded in written representations. At times, as their thinking evolved, they even imitated gestural information that had been made by others during the class discussion. They were progressing toward mutual manifestness.

Gestural and postural feedback were also integral to the formative assessment that guided the teacher's moment-to-moment instructional decisions (Li et al., 2018; Nieminen et al., 2020; Shavelson, et al., 2008). At one point, the teacher called for a gestural response: "I didn't ask you what you know—I want you to guess. *Show me* how high above it would be." The teacher watched the group closely throughout the discussion and could *see* who understood and who did not. When the students became silent, the teacher could see what kind of silence it was—the silence of grappling with a concept, the silence of confusion, or the silence of students waiting for someone else (maybe even the teacher) to just give the right answer.

Translating to the Virtual Learning Environment

Although I have not yet been able to directly observe a similar classroom discussion in a virtual setting such as Zoom, I have spoken with many physics teachers who have taught via videoconference during the pandemic and have had in-depth conversations about their virtual teaching experiences with eleven of them.[1] Most indicated it has been difficult to orchestrate good whole-class discussions in a videoconference setting. Students have been reluctant to unmute themselves.

Some will only communicate by typing in the chat. All teachers reported that their students generally struggled with the physics concepts taught during the distance-learning portion of the course (most of the teachers were teaching electricity and/or magnetism). They indicated that when given a problem, the students approached it mathematically, if at all (many opted out), and few students demonstrated the ability to construct, reason from, or draw conclusions based on representations such as diagrams or equations.

All the teachers I spoke with reported frustration that they could not see most of their students during virtual classes. Many schools and districts required teachers to keep the students' video off during class to protect students' privacy and shield them from the discomfort of allowing others to see their home environment. This was true for over 70 percent of teachers with whom I spoke.[2] Even teachers who were allowed to let students have their video on said that most elected to leave it off. And in cases in which the students had their video on, not much could be gleaned from seeing a tiny picture of a student's face, given the typical class size of twenty or more. Teachers are attuned to assessing student understanding through gesture and posture, but when I asked teachers whether they could think of any situations in which they had obtained information from gestures or body language, only one teacher could give me an example: He helped one of his students use the "right-hand-rule" to solve a problem about a magnetic field around a current-carrying wire. The rest of the teachers with whom I spoke indicated they were not receiving any useful gestural information.

Although many teachers believed there might be more productive discussions among small groups in breakout rooms, most said they were unable to use the breakout feature because school administrators believed that they would be vulnerable to "Zoom-bombing" (unwanted, disruptive intrusions) or that students might do or say inappropriate things if they were in a small group where the teacher could not see or hear them continuously. One teacher, a man teaching at an all-girls high school, said he would not allow his students to turn on their video because he was not comfortable seeing his students in their bedrooms.

While many teachers felt they could competently produce and present lectures and demonstrations for use in online learning, they admitted they lacked the necessary affective feedback to know what, if anything, the students were learning from them. On the whole, the distance-learning environment they described was impoverished with respect to polyvocal (Tobin, 1999) or gestural communicative interaction of any kind.

Conclusion

The vignette provided a revealing glimpse into the nonverbal learning environment in a face-to-face physics classroom. It is readily apparent that

1. Students use gesture as a medium for communicating their spatial information and for making their mental models mutually manifest;
2. The teacher is constantly assessing their developing understanding by attending to both their gestures and their body language; and
3. The teacher makes instructional decisions on the basis of this information.

In the vignette it was clear that in spite of what students were saying, the teacher could *see* they did not understand. By his own admission, the teacher asked them "the same question ten times." Finally, they "got it," and the class moved on. Would the discussion have unfolded this way on Zoom?

This foregoing should not be interpreted as a criticism of virtual learning but rather a challenge. The classroom episode described here is of a good teacher with engaged learners. Student-to-student communication drove the action, and this provided the teacher with a lot of information with which to make his instructional decisions. Can we design virtual learning environments that provide teachers and students with similar affordances?

Perhaps a virtual physics class is better than no physics class at all. However, until we can approximate the learning environment available in a physical classroom with its tools, equipment, whiteboards, and a 360-degree visual and social field, physics students will likely be better served opting for the embodied learning experience of a live rather than a virtual class. Gesture reveals thinking: gestural communication in the classroom gives the teacher access to information about students' thinking and learning that they know but do not *or cannot* say (Goldin-Meadow, 2000). Gesture also enables students to assimilate information even if they are unable to process it lexically. It helps them understand what to pay attention to—what is relevant. The challenge for virtual learning environments in the coming years will be to find a way to help teachers and students have embodied learning experiences even when they cannot be in the same physical space.

Notes

1. Some of these communications were private email exchanges and others were during regularly scheduled Zoom meetings of teachers involved a computational modeling physics first grant-funded project (NSF #1640791).

2. In private communications with 11 different physics teachers, eight indicated that their school or district would either *not require* students to turn their cameras on or *not allow* their students to turn their cameras on.

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IV APPLIED TECHNOLOGY

12 Responsive Teaching for Embodied Learning with Technology

Virginia J. Flood, Anna Shvarts, and Dor Abrahamson

There is growing consensus in science, technology, engineering, and mathematics (STEM) education that the body plays an indispensable role in teaching and learning these disciplines (e.g., Lindgren & Johnson-Glenberg, 2013; Nemirovsky et al., 2014; for a review, see Skulmowski & Rey, 2018). In response, over the last ten years there has been an influx of educational technologies that capitalize on novel human-computer interfaces to deliberately incorporate learners' bodies into the exploration of STEM phenomena. As these embodied learning technologies enter schools and museums, we still know surprisingly little about how educators can support embodied STEM learning with these designs.

Synthesized from our previous studies, we introduce strategies for supporting STEM learning by being responsive to and productively engaging learners' embodied ideas as they use embodied learning technologies. These strategies include (1) attending to learners' embodied action and perception, (2) encouraging the multimodal expression of learners' embodied ideas, (3) repeating and reformulating learners' multimodally expressed embodied ideas, and (4) co-constructing multimodally expressed embodied ideas with learners. We explore these *embodied responsive teaching* strategies (Flood et al., 2020) in the context of two embodied learning technologies for mathematics—the Mathematics Imagery Trainer for Proportion and the Mathematics Imagery Trainer for Parabolas—and demonstrate how they give rise to students' mathematical discoveries.

Technology-Enabled Embodied Learning Experiences for STEM Education

Embodied STEM learning technologies present users with perceptuomotor challenges that invite them to engage in movements, which can lead to new mathematical or scientific insights (Abrahamson et al., 2014; Lindgren &

Johnson-Glenberg, 2013; Nemirovsky et al., 2014). Using computer vision and other advances (see Johnson-Glenberg, chapter 15 in this volume), these systems track and interpret learners' bodily actions, guiding participation by providing feedback about learners' movement and location. Some designs track learners' hand and arm movements, and others track whole bodies in motion (Abrahamson & Lindgren, 2014). To date, technologies have been developed for exploring a wide variety of STEM phenomena. For example, in science education there are designs that allow learners to use their bodies to predict the orbits of meteors (Lindgren & Johnson-Glenberg, 2013), to become the moving particles of different phases of matter (DeLiema et al., 2016), and to experience the impact of changing terrain on animal locomotion (Lyons et al., 2012). In mathematics education, embodied learning technologies support embodied finger-based counting (Jackiw & Sinclair, 2017), the exploration of parametric functions (Nemirovsky et al., 2014), and learners' investigation of ratio and proportion (Abrahamson et al., 2014), among many others.

When learners use embodied learning technologies, they experience new ways of moving and perceiving that constitute *embodied ideas.* These perceptuomotor experiences—the patterns learners notice and the repertoires of movement they develop—are forms of embodied knowledge that are irreducible to the brain and inseparable from the body acting in the world (Abrahamson & Lindgren, 2014; Nemirovsky et al., 2014). Learners are often invited to reflect on and make sense of their embodied ideas with peers and educators, and make connections between embodied experiences (e.g., the sensation of moving through space and time) and cultural forms in STEM (e.g., disciplinary definitions of speed as distance traveled per unit of time, external representations like distance versus time graphs; Abrahamson & Lindgren, 2014). The embodied insights that arise from interacting with embodied learning technologies, however, can be difficult to formulate into words and are frequently expressed *multimodally* using rich configurations of demonstrative action with the interface, gesture, bodily performances, talk, and other semiotic resources (Abrahamson et al., 2014). For educators to support learning and discovery with these technologies, they must pay attention to how learners move and perceive, and also be able to make sense of learners' multimodal expressions of their embodied experiences.

Our work has focused on the practices that experienced tutors use to support students using two different embodied learning designs for mathematics: the Mathematics Imagery Trainer for Proportion (MIT-Proportion; Abrahamson et al., 2014) and the Mathematics Imagery Trainer for Parabolas (MIT-Parabola; Shvarts & Abrahamson, 2019). Both Mathematics Imagery Trainers embody the principles of embodied design (Abrahamson, 2014), in which learners develop physical strategies for achieving a specific goal state. Guided by tutors, learners are invited to share their physical strategies and adopt mathematical artifacts to describe and quantify these strategies (e.g., a Cartesian coordinate system). Through this support, learners are able to make sophisticated mathematical discoveries and reconcile their embodied ideas with disciplinary mathematics (Abrahamson et al., 2012).

The MIT-Proportion provides an interactive context for learners to use bimanual movement to explore ideas related to ratio and proportion. To operate the MIT-Proportion, users lift and lower two independent, handheld Nintendo Wii remotes that move cursors vertically up and down a computer screen (figure 12.1a and b). The screen turns green when the cursor heights embody a set, concealed ratio (e.g., 1:2 depicted in figure 12.1b, shown in light grey). When the cursor heights do not fulfill the ratio, the screen turns red (figure 12.1a,

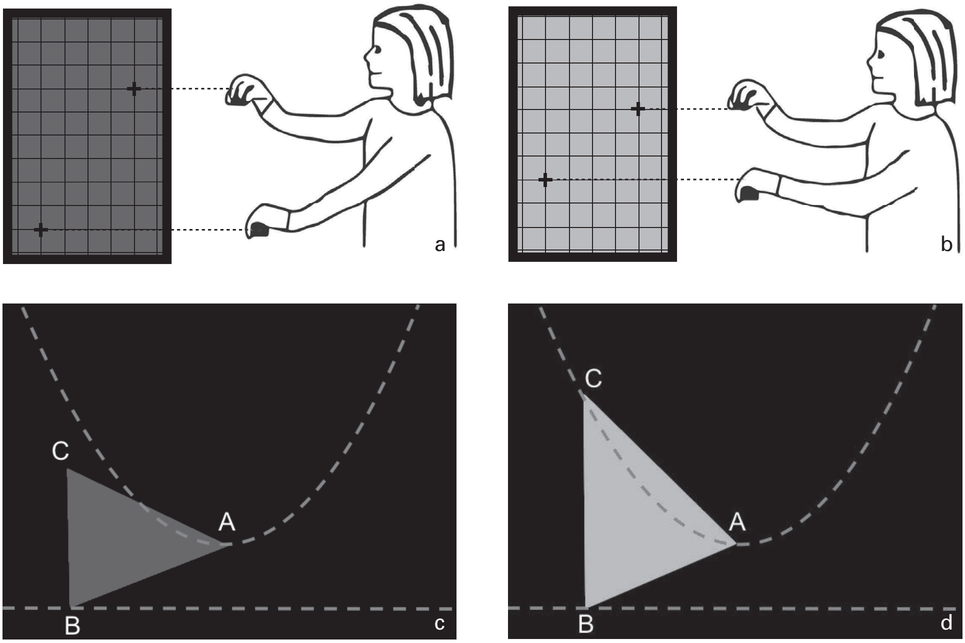


Figure 12.1
(*Top*) When the Mathematics Imagery Trainer for Proportion (MIT-P) is set to a 1:2 ratio, the screen is green only when the right-hand remote is twice as high as the left-hand remote (b, shown in light grey); otherwise the screen is red (a, shown in dark grey). (*Bottom*) In the Mathematics Imagery Trainer for Parabolas, point C is manipulated, point A is fixed (the "focus" of the parabola), and point B runs along a horizontal line (the "directrix" of the parabola). The triangle turns green when point C lies on a parabola (d, shown in light grey); otherwise, it is red (c, shown in dark grey). Lines and letters are inserted for this diagram but do not appear for students.

shown in dark grey). Learners are asked if they can figure out how to turn the screen green and how to keep it green by continuously moving the cursors from the bottom of the screen to the top. By developing and exploring different methods for "making green," learners discover many dynamic patterns and make connections between their physical strategies and challenging mathematical ideas like ratio, proportion, speed, covariation, multiplicative relations, and iterative addition, among others (Abrahamson et al., 2014).

The MIT-Parabola (Shvarts & Abrahamson, 2019), on the other hand, creates an interactive experience for learners to discover the definition of parabolas and explore their properties. Learners move their fingers on a touchpad to manipulate a triangle on a screen, moving its vertex (point C in figure 12.1c and d), and are instructed to try and keep the triangle green. In order to keep the triangle green (figure 12.1d, shown in light grey), unbeknownst to students, they must keep point C positioned so that it is equidistant from a fixed point A (the "focus" of the parabola) and from a point B, which moves along the horizontal line (the "directrix" of the parabola). It also means that the triangle will remain isosceles (two sides of equal length) as the vertex is moved. When point C is not equidistant from point B and A, the triangle turns red (figure 12.1c shown in dark grey). Moving point C to keep the triangle green means that point C (the vertex of the triangle) will move along the path of a concealed parabola that has been preset into the system. Learners are asked to determine strategies for keeping the triangle green as they move point C. Using the design, learners explore a parabola curve as a set of isosceles triangles' vertexes and express the formula of the emerging curve.

Responsive Teaching: Attending to and Engaging with the Disciplinary Substance of Learners' Ideas

To facilitate learners' discoveries and their connections between embodied experiences and disciplinary ways of organizing these experiences, educators must attend to and engage with learners' embodied ideas. In STEM education, the collection of practices that educators use to attend to and engage with learners' ideas is known as *responsive teaching* (Robertson et al., 2016; see also *teacher noticing,* Sherin et al., 2011). Responsive teaching involves (1) drawing out, attending to, and engaging with aspects of learners' ideas that have potential disciplinary value or substance and (2) engaging in ongoing *proximal formative assessment* (Erickson, 2007) (i.e., continuously monitoring students' ideas to adapt instructional support in the moment) (Ball, 1993; Coffey et al., 2011; Pierson, 2008). Students learn more in STEM classrooms where teachers are responsive to learners' ideas (Pierson, 2008; Robertson et al., 2016; Saxe et al., 1999).

A number of specific responsive teaching strategies have been identified in STEM classroom settings. These strategies include eliciting, probing, summarizing, expanding, reformulating, reflecting on, offering interpretations of, clarifying, or highlighting parts of the thinking learners share (Jacobs & Empson, 2016; Lineback, 2015; Pierson, 2008). These classroom-based studies, however, have primarily examined educators' *verbal* forms of responsiveness to students' *verbally* expressed ideas and written work. Few studies of responsive teaching have focused on investigating responsive teaching as an *embodied* phenomenon (e.g., Flood et al., 2015; Flood, 2021), or have examined how educators might specifically adapt these practices to support learners' embodied exploration of STEM with technology. Our recent research on teaching with embodied learning technologies (Flood, 2018; Flood et al., 2020; Shvarts & Abrahamson, 2019) has begun to characterize and document some of the specialized ways that educators can elicit, attend to, and engage with children's multimodally expressed embodied ideas, which we bring together and discuss in this chapter.

Theoretical Approach: Social Interaction as an Arena for Embodied Learning

To understand how responsive teaching strategies create opportunities for mathematical learning through technology-supported embodied experiences, we draw from sociocultural theory, ethnomethodology, and conversation analysis (EMCA; Mondada, 2019), and Goodwin's co-operative action framework (CoAF; Goodwin, 2018).[1] Sociocultural theorist Lev Vygotsky distinguished between children's *spontaneous* interpretations of their experience (e.g., initial patterns and physical strategies within the MIT-Proportion employed to "make green") and *academic* ways of organizing those experiences (e.g., the use of multiplication to predict a series of proportional hand positions to "make green"). Vygotsky believed that social interactions with more culturally competent others are what allow spontaneous and academic ways of organizing the world to grow together and reciprocally shape one another (Vygotsky, 1986). However, Vygotsky did not provide many details about the mechanisms within social interactions between adults and children that make these reciprocal connections possible (Wertsch, 1985).

EMCA and CoAF help us better appreciate how social interactions make these connections possible. EMCA attempts to understand the fine details of the practices people use to build, repair, and maintain a sense of shared meaning moment-by-moment in their interactions with one another (Schegloff, 1991). CoAF (Goodwin, 2018) enriches EMCA by using audiovisual recordings to illuminate the embodied ways in which participants dialogically take up and transform each other's multimodal contributions (e.g., gesture, facial expression, prosody, talk, and so on) to negotiate meanings. Each multimodal utterance a participant contributes is a *substrate* that can be broken down, reused, and reshaped (Goodwin, 2018) in the process of co-constructing new, mutually intelligible ideas from old ones. Together, these approaches help us appreciate meaning-making—where different interpretations of the world (e.g., spontaneous and academic) are brought together—as an *emergent, nondeterministic process* (De Jaegher et al., 2016) that is distributed across different people, their bodies, and the sociomaterial environment in which they are embedded.

In the case of embodied learning technologies, technology-guided bodily actions and experiences comprise a substrate (Goodwin, 2018) that can be cultivated into robust, disciplinary understandings of mathematics through social processes of reflection, negotiation, and signification that occur between educators and learners. By examining these interactions in fine detail, our investigations have been able to reveal a number of practices for attending to and engaging with learners' embodied ideas that facilitate students' mathematical discovery.

Intercorporeal Attunement: Attending to Learners' Embodied Action and Perception

A fundamental aspect of responsive teaching involves making sense of learners' ideas and monitoring these ideas for the seeds of productive disciplinary understandings that can be used to bridge learners' intuitions with more formal concepts and practices (Robertson et al., 2016). Educators must be able to recognize these seeds, even if they initially represent incomplete or incorrect ideas from a mathematical or scientific perspective. Previous studies have examined how educators attend to the ideas that learners share through verbal explanation and inscription (e.g., Pierson, 2008), but very few studies have attempted to understand how educators monitor and make sense of learners' embodied ideas when they are using embodied learning technologies. Educators must continuously attend to not only what learners say but also to learner's movements, their idiosyncratic forms of perception, and their interpretations of their embodied experiences (Abrahamson et al., 2014; Flood, 2018; Shvarts

& Abrahamson, 2019). This *intercorporeal attunement* (Sheets-Johnstone, 2000) allows tutors to reframe learners' attention to perceptuomotor activity at consequential moments so tutors can suggest cultural forms (e.g., disciplinary mathematical ways of describing phenomena) as helpful ways for learners to coordinate their activity and organize their interpretations of embodied experiences (Shvarts & Abrahamson, in press; Flood, 2018).

Using dual eye-tracking, Shvarts and Abrahamson (2019) illustrate a form of intercorporeal attunement, in which tight spatial *coupling* of tutors' and students' perceptuoaction systems dynamically emerge as they work with embodied learning technologies together. In one example a student, Ada,[2] is working with a tutor moving the vertex of the MIT-Parabola triangle searching for positions that turn the triangle green. At first, both Ada and the tutor's gaze follow the path of the triangle (figure 12.2a). A little later, however, Ada develops a specialized way of organizing her movements: instead of watching the path the triangle takes through space, she begins to keep her gaze along the median of the triangle (an imaginary segment that extends from the triangle's vertex to the opposite side, splitting it in half) as she is moving the vertex (figure 12.2c). Notably, the tutor is able to anticipate Ada's perceptuomotor switch. Before Ada begins attending to the median, the tutor herself begins attending to the median (figure 12.2b).

Coupling with students' performances makes it possible for tutors to detect when effective perceptuomotor strategies have emerged and allows tutors to distinguish critical moments for intervention. In this example, attending to the median is a helpful perceptuomotor strategy for dynamically maintaining an isosceles triangle (two sides of equal length), which will keep the triangle green as the vertex is moved. This will also result in the vertex being moved along the path of the "secret" parabola. After anticipating Ada's switch, the

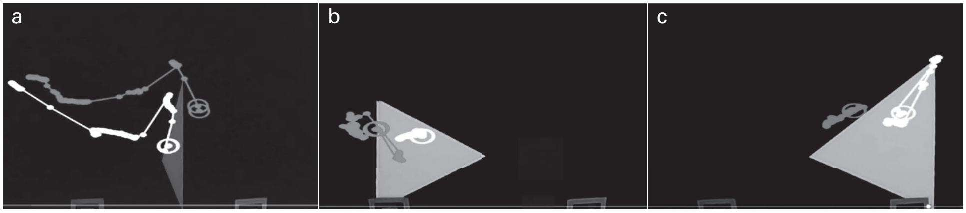


Figure 12.2
(a) Ada and the tutor's eye movements (Ada in white, the tutor in grey) synchronously follow the movement of the triangle as Ada moves the vertex. Later (b) the tutor attends to the median of the triangle before (c) Ada begins attending to the median of the triangle. In (a) the triangle is red (shown in dark grey) and in (b) and (c) the triangle is green (shown in light grey).

tutor asks Ada to reflect on her strategy to keep the triangle green, reframing Ada's attention in this moment toward cultural forms of perceiving and expressing the strategy. In response, Ada is able to articulate the isosceles quality of the triangle she is manipulating.

When educators recognize the disciplinary potential in learners' ways of moving, perceiving, and interpreting embodied experiences, opportunities arise to connect learners' embodied ideas with mathematical ways of organizing those ideas. Coupled as an intercorporeal system with students and the device, tutors seem to be able to vicariously experience learners' perceptuomotor experiences from the learners' point of view (Shvarts & Abrahamson, in press).

Goodwin (2018) has argued that skilled actors (e.g., senior surgeons) are able to inhabit the actions of the newcomers with whom they work, perceiving as newcomers and being in a state of bodily readiness to anticipate what moves the newcomers will make next. However, such intercorporeal attunements are not always readily achieved and can require additional interactional work. In the next sections, we describe three additional practices educators use to elicit and engage with learners' multimodally expressed embodied ideas in order to help lead users of embodied learning technologies towards new discoveries.

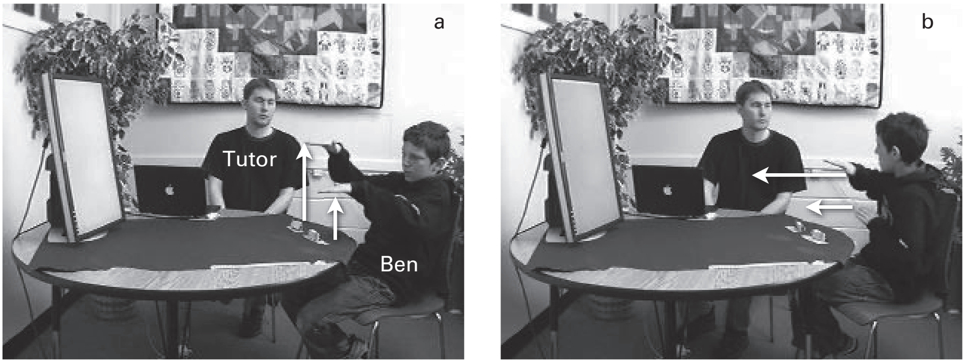
Encouraging the Multimodal Expression of Learners' Embodied Ideas

As part of responsive teaching, educators try to provide opportunities for learners to share and reflect on their reasoning (Robertson et al., 2016). Doing so makes it possible for learners to clarify and elaborate their ideas and also allows educators to better understand learners' ideas so they can effectively adapt their support in the moment (proximal formative assessment; Erickson, 2007).

Learners, however, often know more than they can express in words, and sometimes the words they use to describe their ideas can mislead (Crowder, 1996; Flood et al., 2015; Roth & Lawless, 2002). Both in and outside of embodied learning environments, nonverbal aspects of learners' explanations can contain discrepant, "mismatched" information when compared with verbal aspects (e.g., Alibali & Goldin-Meadow, 1993). In technology-enabled embodied learning environments, embodied ideas—drawing on tactile and kinesthetic experiences, and containing complex, dynamic spatial information—are especially challenging for children to articulate. In addition, learners themselves may often still be making sense of and organizing their experiences as they try to express them multimodally (Crowder, 1996). As a result, a key approach for being responsive to learners' embodied ideas involves finding ways to elicit these ideas in modalities beyond speech and being on the lookout for ways gesture is nonredundant to or mismatched with speech (Flood et al., 2015).

We present an example from previous work (Flood et al., 2020) to illustrate this embodied responsive technique. Ben, a middle school student, is working with two tutors to try to determine how to turn the MIT-Proportion's screen green. Unbeknownst to Ben, the MIT-Proportion is set to a 1:2 ratio. Ben shares a theory for producing green feedback that is difficult to interpret. He says, "My right hand is sort of the pinpoint sort of thing, so . . . , and then to keep it green you have to even them out, I would say." The tutor is responsive to Ben's ambiguous but potentially promising idea for how to make green, and he explicitly encourages Ben to use his hands, stretched out flat without the remotes, to explain what he means.

When encouraged to gesture, Ben is able to provide a physically accurate demonstration of how his hands need to move to make the screen: his right hand rises approximately twice as fast and ends up twice as high (figure 12.3a). Verbally, however, Ben describes his hands as "even apaced" and "going at the same pace." The tutor is responsive to this mismatch between Ben's gestured demonstration and encourages him to elaborate. In response, Ben uses his hands again, but this time he evokes the analogy of two cars traveling a horizontal trajectory where one is going "twenty" and one is going "fifty." He describes this as going "the same speed limit" (figure 12.3b).



"you keep them going even apaced"

"If you wanted to do this with a car, it would sort of be the same speed limit"

Figure 12.3
After being encouraged to use gesture to explain his idea, (a) Ben uses his hands to show how the remotes must move "even apaced" although he moves his hands at different speeds. When asked to elaborate, (b) he describes his hands as being like cars moving at the "same speed limit" going "twenty" and "fifty." Underlined speech corresponds with gesture.

By only paying attention to Ben's initial verbal explanations ("even them out," "same pace") it would be easy to conclude that Ben believed (incorrectly) that the remotes have to go the same speed to make green. However, by encouraging Ben to use his hands to explain his idea further, the tutors created an opportunity to better understand Ben's embodied idea and let it evolve. With his continuing multimodal explanation, Ben explores a disciplinarily valuable idea: the remotes have to move at two *different* yet *constant* speeds. By eliciting and probing Ben's gesture, the tutors were able to make sense of the apparent mismatch between Ben's speech ("even apaced," "same pace," "same speed limit") and his gesture. Instead of correcting Ben, the tutors adjusted their instruction in the moment and made space for Ben to pursue the idea. Ben's new productive car analogy emerged from his exploration and reflection on his own gestured movements. These gestures, elicited by the tutors, became a *substrate* from which Ben could build.

Encouraging students to "explain an idea in your own *hands*" provides productive opportunities for reflection on embodied ideas: Through this reflection, learners are able to reformulate and elaborate their initial utterances in ways that demonstrate new clarity or specificity, and sometimes they are able to make new discoveries/realizations like Ben's car analogy.

Revoicing and Reformulating Learners' Multimodally Expressed Embodied Ideas

In addition to eliciting students' contributions, another crucial aspect of responsive teaching is taking up and reformulating learners' ideas in order to help them extend and connect these ideas with new STEM disciplinary understandings. One way to achieve this is through the practice of *revoicing* or *recasting* learners' contributions. In revoicing, educators repeat (report or restate verbatim), reformulate (modify the content of), and/or elaborate (add new content to) ideas learners have shared (O'Connor & Michaels, 1996). This practice can serve a number of purposes, including (1) highlighting particular elements of students' ideas while backgrounding others, (2) helping students adopt disciplinarily normative language and representations, and (3) extending and reshaping the content of students' contributions to resemble disciplinarily normative concepts (Forman & Ansell, 2002; O'Connor & Michaels, 1996).

Revoicing has been studied primarily as a verbal phenomenon. Yet, when working with embodied learning technologies, learners do not just share ideas with words, but do their best to capture and represent their embodied experiences of interacting with the system, drawing on multiple modalities like full-body reenactments, gesture, and demonstrative action with the device. What

Table 12.1

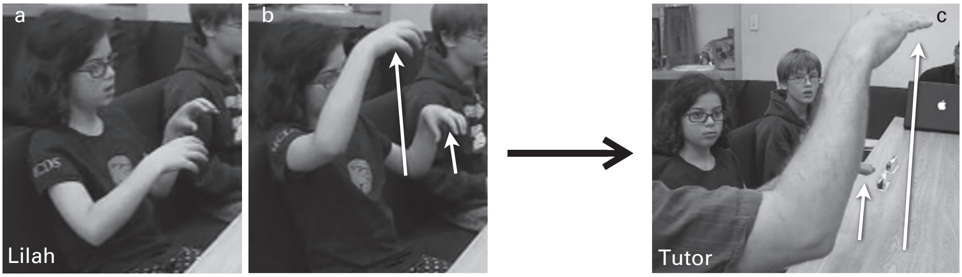
	Repeat gesture	Omit gesture	Elaborate gesture	Modify gesture
Repeat talk				
Omit talk				
Elaborate talk				
Modify talk				

does responsive revoicing look like in this context? When learners share ideas in multiple modalities, there are a number of different ways educators can re-“voice” what has been shared (Flood, 2018). They can repeat, elaborate, omit, or modify parts of learners’ speech or gesture (table 12.1). For example, an educator might repeat a learner’s gesture, but elaborate on their speech, adding a vocabulary word to describe what was represented in gesture (Shein, 2012). Gestures, like sentences, have different phrases or parts to them (Kendon, 2004), and educators also repeat and reformulate gestures by adding, omitting, or modifying gesture phrases (Flood, 2018).

We illustrate gesture reformulation with an example from Flood (2018) and demonstrate how revoicing gestures can help learners make connections between their multimodally expressed embodied ideas and disciplinary ideas. With the help of some tutors, Lilah and a peer are working with the MIT-Proportions with the concealed ratio setting of 1:2. The children have already reported two strategies for “making green:” (1) ensure that the right hand is always *double as high* as the left hand; or (2) move the hands with the right hand rising *double as fast* as the left hand. One of the tutors asks whether there is any connection between these strategies. Lilah volunteers an answer, and her response is composed of talk and an elaborate multipart gesture that has a variety of distinct gesture phrases (figure 12.4a and b).

As Lilah says “that one” she points to the right hand remote. Then, as she continues to speak, she holds her hands out in front of her as if holding phantom remotes. When she says “same time” she holds her hands level at chest height (figure 12.4a), and when she says “would have to go faster” and “lift higher,” she raises her hands so that the right hand travels approximately twice as fast and ends up approximately twice as high (figure 12.4b). Overall, Lilah’s embodied performance accomplishes the idea that the right hand remote is going faster because it must go higher at the same time.

One of the tutors uses gesture and speech to revoice and reformulate Lilah’s idea, treating her initial utterance as a *substrate* and reusing and transforming



"if you're going to do it like, at the same time [a] that one would have to go faster [b] to like end at the same time [a] that one would have to [b] lift higher"

"it has more ground to cover" [c]

Figure 12.4
Lilah's explanation of "faster" has two gestural phrases that she repeats twice: (a) she holds both her hands at the same height, and (b) then she pantomimes a motion with curled hands that would produce green feedback. (c) The tutor's revoicing turn reformulates Lilah's explanation by repeating only one of her gesture phrases, using flat hands, and co-timing it with a new verbal description. Underlined speech corresponds with gesture.

it (Goodwin, 2018). The tutor reenacts Lilah's gesture moving his right hand so that it travels twice as fast as his left hand and ends up twice as high (figure 12.4c). However, he also reformulates Lilah's gesture: He changes the shape of his hands, flattening them instead of pantomiming the operation of the remotes. He also simplifies the hand movements, omitting gesture phrases where Lilah held her hands at the same height. Finally, he also modifies Lilah's speech, saying that the right hand has "more ground to cover" than the left, which could describe horizontal or vertical distance.

The tutor's reformulation decontextualizes Lilah's explanation in both gesture and speech to be less situated in the details of the device, and presents a more generalized disciplinary definition of "faster" as *greater distance traveled during the same amount of time.* Although some aspects of Lilah's multimodal explanation were reformulated, the visible repetition of part of her gesture serves as bridge for Lilah to recognize the similarity between her idea and the tutor's reformulation. After the revoicing, Lilah adopts the tutor's reformulated version of what faster means into her explanation of how to make the screen green.

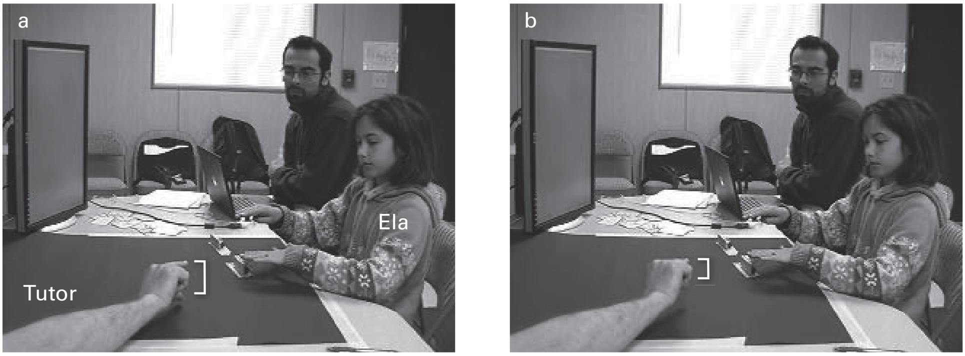
Overall, this example illustrates how reformulating learners' multimodally expressed embodied ideas can be a powerful responsive teaching strategy for highlighting what parts of learners' representations of embodied experiences are relevant to how scientists and mathematicians might think about representing the situation.

Co-constructing Multimodally Expressed Embodied Ideas Together

Another way that educators can take up and build on learners' ideas is by directly interacting with the gestures that learners produce when describing their embodied experiences with embodied learning technologies. Educators and learners can contribute to *the same gesture* as part of co-constructing a multimodally expressed embodied idea together. As an embodied responsive teaching strategy, educators can interact with an unfolding student gesture by (1) highlighting aspects of the gesture (Flood et al., 2015) or (2) contributing new dynamic gestural imagery to the gesture (Flood et al., 2020). By co-constructing gestures, educators can help steer and formulate ideas in productive new directions, while at the same time keeping these new directions grounded in learners' initial observations and ideas. We present an example from Flood et al. (2020) of a tutor and learner co-constructing an embodied, dynamic representation together through gesture.

Ela and two tutors are working with the MIT-Proportion set to a 2:3 ratio. After being encouraged, Ela uses her hands to gesturally demonstrate her discovery of how to make the screen green: she raises her left hand one unit; then, to locate the right hand, she raises the right hand one and a half units. With her iterative 1-to-1.5 method, Ela is able to predict a number of height pairs that go together such as 1 and 1.5 units, 2 and 3, and 3 and 4.5, but she gets stuck predicting larger numbers and cannot predict where the right hand would be if the left were on 10 units. The tutor sees an opportunity to build on Ela's multimodally expressed embodied 1-per-1.5 idea and transform it into multiplicative understanding. He instructs Ela to keep her hands outstretched but instead of iteratively raising each hand by units, he suggests she try positioning the right hand one and half *times* as high as the left hand. He instructs her to lift her left hand about six inches off the desk, and then to put her right hand at a height that is the same height as the left hand plus another half of that height (figure 12.5) so the height of the right hand is one and a half *times* as much as the left hand.

The tutor also uses his own hand to contribute additional dynamic imagery to co-construct a multimodal embodied representation with Ela when she struggles with the embodied multiplicative strategy. She gets stuck when the tutor asks her to predict where the right hand would be if the left hand is at two units.[3] As she hesitates, the tutor reaches into Ela's gesture to lend an extra hand (both literally and figuratively). He makes a pinch shape with his hands to bracket the height under Ela's left hand, which she has raised to two units (figure 12.5a), then he decreases the height between his thumb and index



Tutor: "If you take two, and take half of two, which is one, so it's. . ."

Figure 12.5
The tutor reaches in to Ela's gesture to co-construct a multimodally expressed embodied idea about multiplication. (a) He makes a pinch shape under Ela's left hand, and then (b) shrinks it by half and moves his hand toward Ela's right hand. Underlined speech corresponds with gesture.

finger by about half and slides his hand towards Ela's right hand (figure 12.5b), saying, "If you take two, and take half of two, which is one, so it's . . ." By contributing this dynamic imagery to Ela's gesture-in-progress, the tutor helps her find the correct one-and-a-half times position for her hand. Ela finishes the tutor's sentence, correctly answering "three." The tutor's interaction with Ela's gesture impacted her understanding, and she later applies the same shrinking pinch gesture to illustrate a new situation when she compares the relationship of the speeds of the two cursors.

Together Ela and the tutor have co-constructed a dynamic, embodied way of representing the relationship between the left- and right-hand heights, using iterative addition and then multiplication. Ela's initial gesture, demonstrating iterative addition, serves as a *substrate* that is taken up and simultaneously transformed by the tutor, allowing the tutor to instruct Ela on how to experience her gestured demonstration as a functional multiplicative relation between the heights of the left and right hand. Overall, co-constructing a gesture with learners is a useful responsive-teaching strategy to build from and elaborate learners' initial embodied ideas (e.g., Ela's additive scheme), thus connecting them with new disciplinary understandings (e.g., the functional multiplicative scheme the tutor and Ela co-construct).

Concluding Remarks

Embodied learning technologies pose unique challenges for instructional practice by embracing learners' hands and full bodies as the primary instruments of

STEM learning. Educators must find ways to responsively guide learners toward disciplinary understandings, starting with the *substrate* of learners' spontaneous, embodied experiences of perceiving and moving as they operate the devices. In this chapter, we presented four ways that educators can attend to and engage with multimodally expressed embodied ideas to support learners' mathematical discoveries as they use embodied learning technologies. Drawing on EMCA, CoAF, and sociocultural studies, our fine-grained investigations contribute to filling current gaps in our understanding of how learning can be facilitated with digital technologies that deliberately incorporate the body into STEM learning. In addition, our work has implications for instructional practice by suggesting effective multimodal discursive moves instructors can adopt to facilitate meaning-making with embodied learning technologies.

Although we have discovered these embodied responsive teaching practices in the case of mathematics, we conjecture that these practices would also have utility in other STEM learning domains. Responsive teaching that attends to and engages with learners' embodied ideas is, itself, an embodied practice that involves recruiting one's own body to make sense of learners' perceptuomotor activity, to repeat and reformulate leaners' gestures, and to co-gesture. Future research could investigate teachers' embodied learning of responsiveness (i.e., how teachers come to adopt embodied practices of attending to and interpreting learners' multimodally expressed embodied ideas). For example, the role of mirror neurons (see Butera & Aziz Zadeh, chapter 16 in this volume) could be examined. In addition, the collection of practices we have presented here are not comprehensive, and we hope our work will open up additional investigation into the embodied dimensions of responsive teaching with educational technology.

Notes

1. Sociocultural theory, developed by Lev Vygotsky, is widely used in the fields of psychology and education. It is an approach to understanding learning and development as fundamentally entwined with and emerging from social interactions embedded in particular cultures, places, and times. Ethnomethodology and conversation analysis (EMCA), on the other hand, come from sociology and investigate the systematic practices people use to create social order as part of everyday life. Ethnomethodology (which means "people's methods") originated with the sociologist Harold Garfinkel; conversation analysis, an offshoot that focuses specifically on conversational practices, was introduced by the sociologists Harvey Sacks, Gail Jefferson, and Emmanuel Schegloff. Drawing on both of these approaches, the co-operative action framework (CoAF), developed by linguistic anthropologist Charles Goodwin (who trained with Gail Jefferson), synthesizes sociocultural theory, EMCA, and semiotics to explain how meaning-making, coordinated social activities, and human artifacts are all made possible through human beings' propensity to decompose, reuse, and transform the resources others have introduced into public arenas across multiple scales of time.

2. All student names are pseudonyms.

3. This is good evidence that Ela is earnestly trying to understand Dor's proposal, since earlier predicting 3 from 2 was no problem with her original iterative strategy (raising the left hand one unit and the right unit one and half units).

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13

The Need for SpEED: Reimagining Accessibility through Special Education Embodied Design

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Making learning media accessible to learners with non-majority sensory profiles is often conceptualized as presenting information in an alternate format, such as providing auditory descriptions of visual images. This definition presupposes that information remains fundamentally the same regardless of how media are used. A blind learner[1] might use a tactile version of a visual diagram, or a Deaf learner might access a spoken lecture through a sign language interpreter; at first glance, these students may be thought to access identical educational content to their peers. They benefit from state-of-the-art accessibility solutions, yet we propose that these students are not yet being granted fully equitable access to content. Emerging evidence from the embodiment turn in the cognitive sciences suggests that our bodily engagements with the world shape our cognitive structures (Fincher-Kiefer, 2019). What you see may be what you get, but what you hear, touch, or move might get you something else.

Educational design frameworks implicitly or explicitly take up extant theories of cognition and learning. As embodied cognition theory garners traction, we propose that it is necessary to rethink accessibility for students with sensory differences from this new theoretical perspective. The result of this reimagining is a new framework for design and design-based research that we term *Special Education Embodied Design* (SpEED). In many ways, SpEED is complementary to current accessibility frameworks and provides a means to develop more specific tools for accessibility. At the same time, SpEED's different theoretical foundations take accessibility in new directions.

In this chapter, we present SpEED as a new design-based research framework. We begin by describing the Universal Design for Learning (UDL) framework and its theoretical underpinnings. We then discuss how embodied cognition and its derivative design framework, embodied design (Abrahamson, 2014; Abrahamson et al., 2020), can provide a productive rethinking of these theoretical underpinnings, drawing upon each framework to form SpEED.

We introduce the core principles of SpEED and illustrate them with four SpEED projects, each developed for a different student population currently served within special education. Setting forth from the precedent of the UDL framework, we show how SpEED illuminates a new perspective on accessibility. We conclude with a discussion of where SpEED might go next.

The UDL Framework and Cognitive Neuroscience

Universal design began in architecture as a paradigm for providing equitable access to physical spaces (Mace et al., 1991; see also Goldsmith, 1997). UDL took up this mantle in education to guide educators in embracing individual differences in students' learning needs, abilities, styles, and preferences (CAST, 2018; Rose & Meyer, 2002; Meyer et al. 2014). The educational framework uses a variety of teaching methods to remove any barriers to learning and to give all students equal opportunities to succeed. In UDL, differences are flexibly accommodated through proactively offering students diverse representations, modes of expression and action, and means of engagement.

UDL takes up a view of learning rooted in cognitive neuroscience. The design principles of UDL are defined according to the three primary sets of brain networks activated during learning: recognition networks, strategic networks, and affective networks (e.g., Kandel et al., 2000; Damasio, 1994, as cited in Rose & Meyer, 2002, chapter 2). The recognition networks, including the visual and auditory cortexes, categorize information. These gave rise to the UDL principle of *multiple means of representation.* The strategic networks, including the frontal lobes of the brain, organize and express thoughts and ideas. These yielded the principle of *multiple means of action/expression.* The affective networks, including the limbic system, drive a learner's excitement and motivation. This final set gave rise to the principle of *multiple means of engagement.* We suggest that the use of neural networks as organizing principles for UDL reflects dominant views at the time of UDL's inception that mind and body are separable and that cognition is strictly the domain of the brain (Thagard, 2019).

The Embodied Design Framework and Embodied Cognition

Distinct from the implicit neural theoretical foundations of UDL, embodied cognition shifts from understanding cognition as based primarily in the brain to understanding it as including and emerging from the body and bodily activity (Newen et al., 2018; Shapiro, 2014). In this chapter, we will limit our scope to one lineage of embodied cognition of broad relevance in education: enactivism.

Enactivism posits that the material body-in-action forms the foundation of the mind (Hutto & Myin, 2012). Perception consists of perceptually guided action (Varela et al., 1991): we make sense of sensation through our actions in the world. Rather than a sequential process where sensation triggers processing and consequently action, perception and action mutually inform one another moment to moment in a *perception-action loop.* With repetition, the sensorimotor patterns supporting action give rise to cognitive structures.

Such an understanding of thinking and learning frames the ways we design in qualitatively different ways: the body itself becomes a primary instructional resource. Embodied cognition has inspired educational designs that use the body in new ways (e.g., Kelton & Ma, 2018; Nathan, 2014; Sinclair & Heyd-Metzuyanim, 2014; Vogelstein et al., 2019). The embodied design framework (Abrahamson et al., 2020; Abrahamson, 2014) codifies implications of enactivism for educational design. Embodied design aims to create the conditions for new sensorimotor schemes to emerge. Designers start from learners' existing resources, including their sensorimotor capabilities and innate capacity for certain perceptual judgements. Designers then render target concepts as a phenomenon that learners can explore using their existing resources. Disciplinary forms such as symbolic artifacts and measurement instruments are then introduced as potential tools to enhance the regulation, evaluation, or explanation of learners' initial responses.

Embodied perspectives are yielding meaningful reanalyses of disability (de Freitas & Sinclair, 2014; Lambert, 2019; Toro et al. 2020; Yeh et al., 2020) and UDL (Abrahamson et al., 2019). Building upon Abrahamson and colleagues (2019) prior efforts to enrich UDL through enactivism, we aim to crystalize embodied cognition into a framework for accessibility-focused design-based research.

SpEED Principles

SpEED reimagines accessibility from an embodied cognition perspective. It shares both UDL's commitment to proactive, adaptive education and embodied design's commitment to grounding in students' specific embodied resources.

SpEED sets forth from the following theoretical and ideological commitments.

1. *Learning happens through the body's sensorimotor engagement with the world.* SpEED roots in embodied theories of cognition and learning, which posit that the nature of sensorimotor engagement fundamentally shapes the learning that takes place.

2. *Learning begins from learners' existing embodied resources.* Embodied resources include prior sensorimotor experiences, practices, processes, and abilities.

3. *Instruction must flexibly adapt to learners' sensorimotor diversities.* This principle takes up disability studies' commitments to embrace human variation, challenge notions of normalcy, and recognize the social nature of disability (Ferguson & Nusbaum, 2012). SpEED actively centers learners whose educational potential could be further targeted in the general education classroom. It requires attention to how learners vary in their sensorimotor experience and how such diversities give rise to different cognitive architectures.

SpEED is a design-based research framework with a strong commitment to bridging theory and practice (Tancredi et al., 2020; Tancredi et al., 2021). The design-based research approach allows SpEED to both develop new useful practices (Odom et al., 2005) and create new contexts within which to empirically test embodied cognition theory (Cobb et al., 2003).

SpEED Parameters

Drawing on literature around multimodality and embodiment, we define three physical factors as key parameters of SpEED: media, modalities, and semiotic modes. *Medium/media* denotes cultural and natural material substrates such as pen and paper, a tablet interface, or the body (Kress, 2001). *Modality* delineates the sensorimotor systems recruited by a task. We include sensory systems such as the visual, auditory, tactile, body in space (proprioceptive), and balance (vestibular) systems, as well as kinesthetic forms of engagement such as manual, oral, or whole body (Edwards & Robutti, 2014). *Semiotic mode* refers to a system of meaning-making (Kress, 2001). These may include spoken or signed language, gesture, or mathematical symbols. Media, modalities, and semiotic modes act as interdependent constraints on the perception-action loop (figure 13.1). In turn, these factors mold what cognitive structures can take shape.

SpEED in Action: Introducing Four Designs

We present four SpEED examples that illustrate how SpEED reimagines accessibility. These four design-based research projects have convergently evolved through research on specific design problems affecting students in special education. In each case, embodied cognition theory has generated new possibilities by offering a new lens on long-standing problems of practice. Each SpEED project has a target population and specific learning design objectives; per SpEED principles, each begins from learners' existing embodied resources to design media that fosters sensorimotor engagement to cultivate

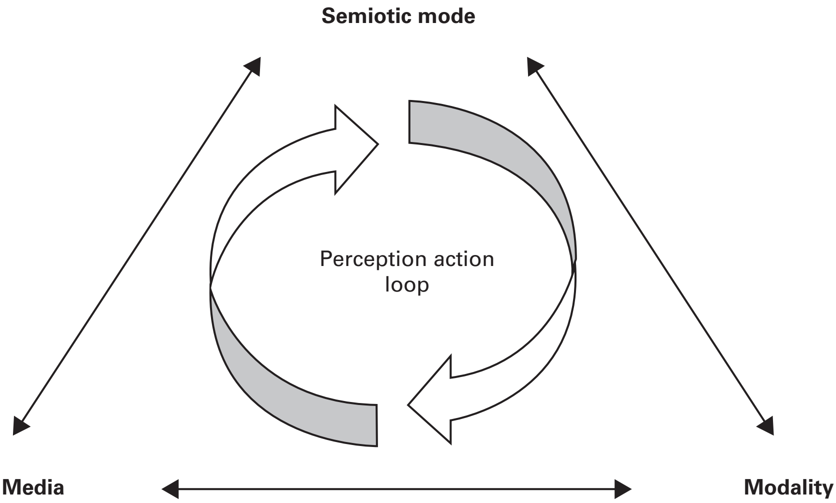

Figure 13.1
Key parameters of SpEED: media, modality, and semiotic modes. Media, modality, semiotic modes, and the reciprocal relations among them constrain possibilities for perceptually guided action.

learning (table 13.1). Three of the four SpEED projects deal explicitly with mathematical concepts; the fourth targets peer interaction. Triangulating across these four distinct populations and contexts demonstrates SpEED's widespread utility to research on accessibility and diversity.

The Balance Number Line

The Balance Number Line[2] (BNL, figure 13.2) re-envisions instruction on absolute value and negative numbers for vestibular-seeking learners. Extant theories in psychology and occupational therapy literature purport that sensory stimulation within an optimal range plays a key role in attention and self-regulation, with the optimal range varying by individual (e.g., Dunn, 1997). Stimulation levels that are comfortable for the sensory majority may be excessive or insufficient for some learners. A number of disabilities including attention deficit hyperactivity disorder (ADHD) and autism[3] (Little et al., 2018) are frequently associated with differences in sensory modulation, so learners in special education are especially vulnerable to sensory mismatch with their learning environment.

Evidence suggests that sensory experience impacts academic outcomes: sensory differences predict academic learning for children on the autism spectrum (Ashburner, Ziviani, & Rodger, 2008), and self-directed movement such as fidgeting positively correlates with performance for children with ADHD (Sarver et al. 2015). Additionally, phenomenological autistic perspectives

Table 13.1
Overview of SpEED projects

	Balance Number Line	Magical Musical Mat	SignEd|Math	Audio-Haptic MIT-P
Target population	Learners who are vestibular sensory-seeking	Nonspeaking learners on the autism spectrum	Deaf (and hard-of-hearing) learners*	Blind and low-vision learners
Design objective	Support learning of negative numbers and absolute value concepts	Facilitate participatory sense-making and spontaneous interaction	Enhance learning of proportionality and fraction concepts	Establish collaboration between students with different sensory access needs in learning proportionality
Embodied resource	Sensory regulatory movement (rocking)	Shared modality of touch	Signs' potential to be iconic and grounded in action/experience	Coordinated movement with multimodal feedback

*Although this design centers Deaf learners, it is also intended to extend to learners who are hard of hearing. Use of American Sign Language as the primary means of communication is the central characteristic of the population the presented design is aligned to.

suggest that sensory stimulatory movements like rocking can be not only regulatory but also expressive and exploratory (Nolan & McBride, 2015). Despite these findings, traditional mathematics classrooms provide limited stimulation opportunities for several sensory systems, notably the vestibular system in the inner ear, which governs balance and orientation. The vestibular system has been implicated in cognitive development (Hitier et al. 2014; Wiener-Vacher et al. 2013) and even abstract conceptual reasoning (Antle et al., 2013). Not only is vestibular engagement neglected in the majority of math activities, but also students' spontaneous vestibular-activating movements such as pacing or rocking can be read as disruptive in the classroom. Thus, vestibular-seeking learners are forced to learn in a suboptimal state of sensory regulation.

The BNL aims to directly incorporate vestibular stimulation into learning activity. It does so by making rocking on a balance board central to a series of exploratory and goal-oriented mathematics learning tasks. Learners sit on a balance board and slide their hands along a number line in front of them. Their movements cause shifts in the board's balance, providing stimulation to the vestibular system that serves as informative feedback about the placement of their hands (for example, –3 and 3 are experienced as being in balance, while –3 and 4 would be experienced as a slight lean to the right). BNL activities include finding a solution for how to move one's hands in balance (the solution involves moving both hands equidistantly from the origin), and later expressing this solution numerically, as well as planning using magnetic arrows and exe-

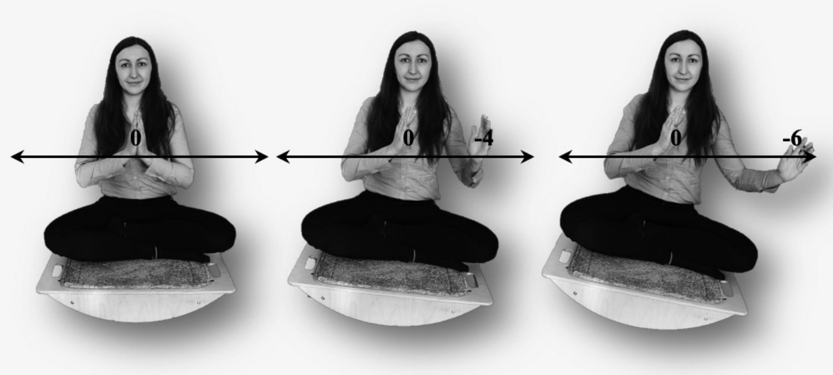

Figure 13.2
The Balance Number Line (Tancredi). Changes in hand position shift the angle of the board as shown. Students sit on the balance board facing a wall and move their hands along a number line on the wall (not shown) such that their vestibular (balance) system provides feedback about their hands' relative distances from zero. Here, the learner's left hand moves toward their left into negative numbers.

cuting arithmetic equations using sliding movements of both hands pressed together, resulting in shifts in the board's tilt.

The design builds upon learners' natural engagement with vestibular stimulatory behavior and uses this as a resource for conceptual learning and understanding. In a pilot study, a vestibular-seeking sixth-grade learner on the autism spectrum engaged the board in hybrid ways: sometimes rocking rhythmically for regulation as during waiting periods, other times acting upon the rocking to achieve matching degrees of tilt to either side, and still other times perceiving mathematical qualities through rocking, as when comparing the absolute value of two numbers by attending to the degree of board tilt for each. The BNL is designed not only to offer respite from vestibular understimulation, but also to use vestibular stimulation as perceptually salient learning-relevant feedback for conceptual learning.

The Magical Musical Mat

The Magical Musical Mat (MMM, figure 13.3) is a domain-general environment that allows people to interact with one another through the nonspeech modalities of touch and sound. Although social interaction is an essential component of any learning context (Vygotsky, 1934/1962), many Autistic learners, especially those who are minimally/nonspeaking, are unable to participate in interaction. Nonspeaking individuals often have to accommodate to their interlocutors' dominant communicative modality—speech—before being

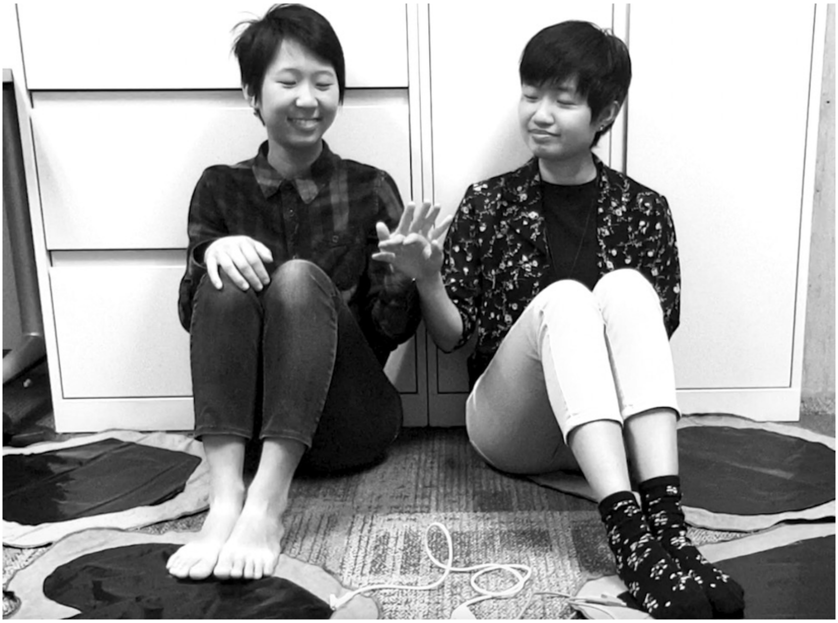

Figure 13.3
The Magical Musical Mat (Chen). Two people have their feet on Magical Musical Mats and touch hands, resulting in dynamically changing sounds as they haptically interact.

deemed a relevant participant within social interaction (Light et al., 2019). The overriding focus on verbal speech is most visible in the design of aided augmentative and alternative communication (AAC) systems and interventions, which are geared toward serving as an alternative to or augmentation of an individual's speech (Beukelman & Mirenda, 2013). Although AAC can support the practical needs of Autistic individuals, their exclusive focus on speech has neglected the body's significant role in joint action (Chen, 2021), thus neglecting the developmental antecedents of communication: reciprocal, affective, and embodied attunement to others (Trevarthen, 2011).

A growing body of testimonials from Autistic individuals (Conn, 2015; Kapp, 2019), supported by scientific research (Behrends, 2012; Dickerson, 2007; Chen, 2016), suggests that Autistic individuals participate in interaction through nondominant modalities. Specifically, another characteristic of Autism—the production of repetitive, rhythmic behavior—has been identified a valuable resource for self-regulation, self-expression, and social interaction (Bascom, 2012, Nolan & McBride, 2015).

The MMM surfaces interpersonal touch as a modality through which musical co-exploration, and as a result, joint rhythmical action, can take place (see also

Chen, 2021). When participants step onto the mat and explore different types of touch interactions together, capacitive sensors in the mat detect their haptic, touch-based interactions, triggering musical sounds. Different types of touch—such as holding hands, high-fives, or gentle taps—offer distinct auditory qualities, resulting in a rich diversity of sound-touch expression. The Autistic students who used this mat in a pilot study explored a variety of touch-based gestures and sounds with their hands and feet, invented rhythmical hand games, and collaborated in pretend play. The practitioners who facilitated the session also noted a behavioral change in some students, for whom play on the mat had a lasting calming effect (Chen et al., 2020). This design project provides a medium for improvisational, creative co-engagement and communication that forms a basis for participatory sense-making (De Jaegher, 2013) in the learning context.

The Mathematical Imagery Trainer for Proportion

The remaining two SpEED projects each reimagine a specific embodied design, the *Mathematics Imagery Trainer for Proportion* (MIT-Proportion) (Abrahamson, 2014). The pedagogical purpose of this design is to support students' learning of the concept of proportional equivalence. Learners encounter an interaction problem wherein they control the vertical position of two cursors on a screen by moving their hands up and down. Whenever the heights of the two cursors correspond to a predefined ratio not known to the student—for example, the right hand being twice as high as the left hand for the ratio 1:2—the screen turns green. Otherwise, the screen is red. The students are first asked to make the screen green, then to do so in another way, and eventually to move their hands continuously in green. Using this feedback, students discover how to move such that the gap between their hands increases as their hand positions rise. This way of moving constitutes a new sensorimotor scheme that grounds proportional reasoning. Disciplinary forms such as a grid and numbers are then overlaid on the screen as means to better control, evaluate, and explain their movements. (See chapter 12 for further discussion of this design.)

SignEd|Math

SignEd|Math redesigns the MIT-Proportion with attention to Deaf learners' experience. The project's central assumption is that learning math through the medium of sign language changes the structure of learning content from both an individual-embodied and a social-constructivist perspective (e.g., Grote et al., 2018; Krause, 2017). There are concerns in Deaf education that Deaf students are often still treated as "hearing students that cannot hear" (Marschark et al., 2011, p. 4) without considering their specific ways of thinking and making sense of the world. At the same time, research in psycholinguistics reports that using sign languages influences conceptual understanding, specifically how concepts and knowledge become structured for the signer (see, e.g., Grote et al., 2018). This raises the question of whether traditional instructional approaches are actually appropriate to best accommodate Deaf students' way of thinking and learning mathematics. SignEd|Math starts to reimagine mathematical instructional approaches starting from the strengths of Deaf students and integrating sign language as a natural resource of Deaf learners.

The SignEd|Math redesign of the MIT-Proportion bridges from action to signed mathematical discourse to carry conceptual meaning from individual sensorimotor experience to social negotiation of meaning. It adopts the original idea of proportional movement and implements it on a touchscreen. Here, learners manipulate the lengths of two bars each spanned by the thumb and index finger of one hand (see figure 13.4). As in the original design, the screen turns green when the lengths of the two bars fulfill a target ratio. Unlike in the original design, the orientation of the bars can be varied on the touchscreen plane. Manipulation with the thumb and index finger is designed to prompt a hand shape called "bent L" in American Sign Language. The bent L is a classifier[4] that is used to refer to a generic number or quantity (Kurz & Pagliaro, 2020), with its concrete integration in a signed expression depending on the

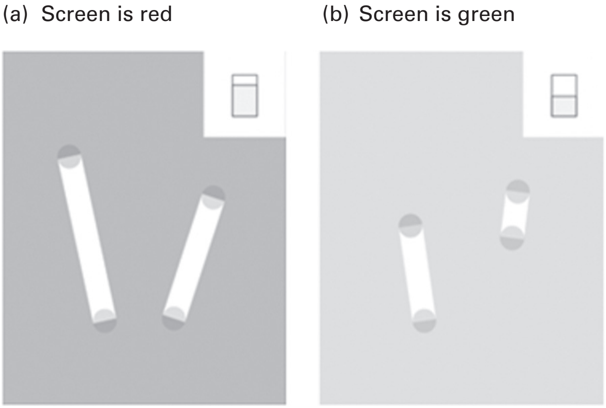
(a) Screen is red
(b) Screen is green

Figure 13.4
Redesign of the MIT-Proportion on tablet interface in the context of SignEd|Math (Krause). The grey dots are touch points that can be moved on the plane, operated by thumb and index finger. The bars span between the touch points such that the lengths of the white bars equal the distance between the thumb and index finger of each hand. The screen turns green when the ratio of the length of the left bar to that of the right bar is 2:1 (b); otherwise, it is red (a). The bar in the upper corner represents an optional extension, linking the relation between the bars to a part-whole relationship (part/whole = length of left bar/length of right bar). To see this in action, visit https://tinyurl.com/SignEdMath-mitp.

context. It hence is not the sign for “number” or “quantity,” but its use can indicate these entities conceptually. In the SignEd|Math MIT-Proportion redesign, integrating the number classifier as a feature in the tablet action attempts to link action, concept, and language in a meaningful way through the idea of “modal continuity” (Krause & Abrahamson, 2020). In this, initial action builds a base for linguistically accurate signed mathematical expression to talk about the embodied experience (Krause, 2019)In a subsequent transfer task, student are invited to collaboratively solve a problem in pairs that elaborates on the notion of proportion first introduced through the tablet activity.

Following socioconstructivist theories, this activity sequence creates an opportunity for shared gestural signs and shared mathematical meaning to be constructed by peers, with the former serving as a preconventional means to address the new mathematical knowledge in development. This process takes advantage of signed languages’ unique potential to iconically incorporate action to ground meaning in activity. Integrating insights from psycholinguistics and deaf education that show an influence of mathematical signs’ iconicity on understanding, the project aims to foster the emergence of conceptually and linguistically generative signed mathematics discourse about the focal math concept.

The Audio-Haptic Mathematical Imagery Trainer for Proportion

A recent project by Abrahamson et al. (2019) examines how an enactivist view of learning can enrich UDL. As an exercise in universally accessible design, the authors pose a redesign of the MIT-Proportion that reimagines how the mathematical construct of proportionality can be represented for sighted and non-sighted learners within a shared activity. The authors critique how commonly used tools such as tactile diagrams and text-to-speech can function as mere replications of visual representations rather than authentic interpretations for spatial understanding. Attempts at shifting learning media from visual to nonvisual formats must be done with consideration for how information might require alternate conceptualization when presented through auditory, tactile, or kinesthetic modalities.

The latest version of the resulting design is the Audio-Haptic MIT-Proportion (henceforth AHM) (figure 13.5). Learners stand on opposite sides of a board featuring knobs in parallel tracks. Peers on either side of the board slide the knobs together. When the ratio of the first knob to the second fulfills the secret ratio, the knobs vibrate, and a sound is produced, functioning similarly to the green color in the original MIT-Proportion design. This design represents proportions with visual, auditory, and haptic feedback such that visual and nonvisual learners achieve equitable independence in their learning and can learn together. The AHM ensures students have equal participation in self-guided and

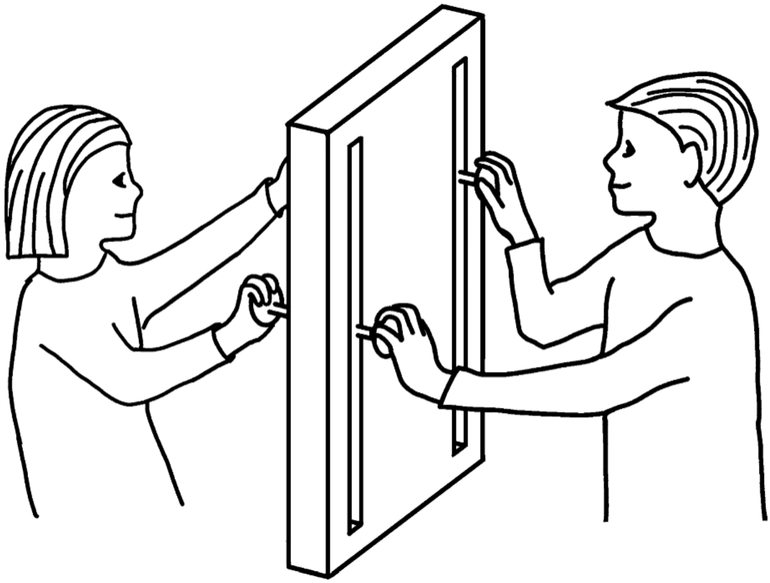

Figure 13.5
The Audio-Haptic Mathematical Imagery Trainer for Proportion (Siu). A blind student collaborates with a typically sighted student to move the sliders in a 1:2 ratio, as guided by visual, auditory, and haptic feedback (Abrahamson et al., 2019). Art: Virginia J. Flood.

coordinated movements, regardless of sensory diversities, optimizing the learning experience for all students.

New Avenues for Accessibility

An enactivist perspective reveals new avenues toward flexible, adaptive education. To map these avenues, we start from UDL and show how SpEED sheds new light on the framework. Rooted in cognitive neuroscience, UDL distinguishes action, representation, and engagement (CAST, 2018). Rooted in enactivism, SpEED highlights the intertwinement of these processes. Through the perception-action loop, action fundamentally participates in perception. Learning from media, then, occurs through learners' actions with those media, such as how a learner moves their eyes over a diagram. This perspective can support greater intentionality in designing for learner actions. For example, consider two activities on graphing: one where a child jumps on a control pad to select a graph from a set of options (for example, jumping on the left pad to select the left image on a screen), and the other where the child's rate of jumping up and down influences the height of a graph (Charoenying, 2013). A given child may be able to participate fully and joyfully in either activity. However, in the former case, the jumping action is incidental to the concept, whereas in the latter, it is directly salient. From an enactivist perspective, concepts themselves must be conveyed through meaningful sensorimotor experience. Beyond the representation/action/engagement divide, SpEED shifts the focus to how educational designs shape perception and action.

SpEED is characterized by reimagining the intertwined factors of media, modality, and semiotic mode underlying learning design (table 13.2). The modalities and semiotic modes available to a given learner population must inform media design. For example, in SignEd|Math, available semiotic modes (sign language and gesture) and modalities (manual kinesthesia) drive the media (tablet application) design. In the BNL, amplifying a given modality (vestibular engagement) shapes media (incorporation of a balance board) in such a way that a new semiotic mode emerges. Traditionally, negative numbers are conceptualized as an extension of the set of natural numbers, but the BNL also establishes a negative number as that which perfectly equilibrates its positive counterpart. By working with the affordances of a given modality, SpEED can generate conceptual restructuration (Wilensky & Papert, 2010) that can envision concepts in new ways.

Interaction Reimagined

SpEED adds greater specification to UDL guidelines for supporting interaction with media and with peers. From an enactivist perspective, feedback informs perceptually guided action on an ongoing basis. UDL guidelines call for feedback to be timely and frequent (CAST, 2018); SpEED must go further to

Table 13.2
Reimagined media, modalities, and semiotic modes in the four SpEED projects

	Balance Number Line	Magical Musical Mat	SignEd|Math	Audio-Haptic MIT-P
Modality	Vestibular, manual kinesthetic, proprioceptive (in mutual interaction)	Auditory, tactile, and kinesthetic	Visual-dynamic, manual kinesthetic	Auditory, tactile, and manual kinesthetic
Semiotic mode	Balance board position and hand movements	Locally developing sound and touch based semiotic modes	Locally developing signs grounded in action, integrated into sign language	Independently coordinated movements guided by audio-haptic feedback
Media	Balance board and number line	Mat and bodies	Manual interaction with tablet, signed conversation	Sliding haptic handles and audio indicators

maximize the consistency and immediacy of the relationship between action and result. In all four of the SpEED designs, feedback is provided at an instantaneous timescale through sensory feedback in one or several modalities available to the learner, be it haptic (vibrating dials in the AHM), auditory (music from touch on the MMM and sonification in the AHM), vestibular (tilt of the balance board in the BNL), or visual (change in color in SignEd|Math). The MMM in particular sets itself apart from other solutions in its domain in this regard: AAC devices typically involve a delay between intention and expression in that a sequence of motor actions must be undertaken to select referential symbols for speech generation. By contrast, the MMM offers interactional immediacy, allowing students to be fully co-present with their peers. In SpEED, feedback is the means by which learners develop and refine new sensorimotor schemes.

SpEED also reframes interaction with peers. Learning is inherently situated in social practice, whether teacher-to-student or peer-to-peer (Vygotsky, 1934/1962). UDL guidelines stipulate that educators should foster collaboration and community by supporting peer interaction (CAST, 2018). SpEED expands upon this perspective by embracing interaction beyond the dominant modalities of speech and the linguistic system to include all sense-making practices involving two or more people. This is exemplified in the MMM, which centers nonspeaking individuals on the autism spectrum for whom verbal language is not a dominant semiotic mode. The nonspeaking student often has to participate in interactions where speech is used by others and where speech generation is expected of them. Designing for touch-based interactions surfaces a mode of interaction available to most—touch—such that nonspeaking students and their neurotypical peers can interact through the same communicative modality (Chen et al., 2020). Through the modalities of touch and sound, the MMM creates a platform for joint attention and co-enactment, fundamentals of social interaction that underlie language production. Rather than adopt predefined semiotic modes, the MMM creates a context within which novel meanings can emerge through joint action. Participants on the mat repeat and adapt movements to jointly create sound events and thereby develop new semiotic modes. This creates a baseline that starts from what individuals can do rather than starting from translating higher order skills emerging from a different developmental trajectory. Through focus on the body, SpEED can offer alternative ways for peers to access interaction.

The AHM and SignEd|Math expand the role of peer interaction to serve as a means of concept construction. Peers interact with a movement-based activity and engage in discourse together about that activity. Coordinated engagement in joint tasks gives rise to mathematical meaning. In the AHM, peers coordinate so that one slider moves at twice the rate of the other. Through performing this coordination, they identify and articulate key properties of proportionality. In SignEd|Math, peers collaborate to solve a problem that builds on their earlier work with the tablet activity; in so doing, they come up with signs to refer back to the former activity and negotiate new meaning. These signs constitute the situated vocabulary for generalizing the mathematical concept encountered in the activity and therefore ground the social discourse in individual concept formation. SpEED occasions dynamic sensorimotor interactions, and through these interactions, access to concept construction.

Surfacing and Challenging Modalism

Special education populations frequently engage the world in ways that differ from neurotypical individuals through modalities that are not traditionally privileged as ways of learning. An enactivist approach calls for semiotic modes that grow from learners' embodied practices in these modalities. Indeed, this theoretical orientation brings to light a new issue of *modalism:* the practice of privileging certain modalities over others and ignoring other possible modal constitutions. We use the term modalism here in the lineage of such terms as ableism, audism, and oralism, wherein specific sensorimotor configurations and modes of interaction are granted supremacy. UDL guidelines invite the use of multiple or alternative modalities (visual, tactile, auditory) and media (sign language, text, physical objects) (CAST, 2018). SpEED offers a means of evaluating the pedagogical and epistemic value of alternative forms. As an example, the AHM challenges the impoverishment of learning materials available to blind students, occasioned by instruction's occulocentrist history (Abrahamson et al., 2019). Learning materials are frequently purported to achieve accessibility when in fact they merely translate visual-based spatial reasoning instruction through other modalities, as a tactile version or description of a graph might do. These media maintain vestiges of the semiotic modes of their original visual-based medium. In contrast, the AHM puts forth a means of rethinking what the concept of proportionality is by setting forth from the ways nonvisual learners dynamically engage with the world. Similarly, SignEd|Math, for example, refuses to mimic the semiotic modes of spoken language in sign language, recognizing that sign language is changing the way Deaf learners structure their experiences and knowledge. (Grote et al., 2018; Krause, 2019). To be accessible, semiotic modes must emerge from dynamic interactions in modalities available to an individual.

Conclusions and Discussion

The SpEED design-based research framework reimagines accessibility from an embodied cognition perspective. In this chapter, we use one lineage of embodied cognition, enactivism, as a starting point toward this reimagination. By establishing roots in the learner's embodied resources and attending to the interrelation of media, modalities, and semiotic modes, SpEED generates designs for interaction and conceptual learning that subvert modalism. Although SpEED research remains in its infancy, the four early stage SpEED projects show that SpEED can offer a foothold on diverse design problems in special education.

Critically, SpEED research also offers a means to evaluate embodied theories of cognition and learning across diverse populations. The SpEED projects presented here show promise for bringing together embodied perspectives, semiotics, and socioconstructivism. Future work in SpEED should expand upon other strands of embodied cognition theory beyond enactivism, such as dynamical systems theory and extended cognition, to analyze how these might reshape accessibility. Moving forward, in addition to expanding work on sensory diversity and learners of different profiles learning together, SpEED research must also address motor differences. As SpEED takes on a broader range of design problems, it is poised to reevaluate epistemological assumptions within and beyond the discipline of mathematics.

The need for SpEED is by no means exclusive to special education. These populations are merely a critical starting point for incorporating the sensorimotor diversities present in any classroom. When reevaluated from an embodied perspective, dominant practices in general and special education classrooms are not yet providing deep disciplinary engagement to all learners. SpEED offers a pathway toward building truly equitable learning opportunities.

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Notes

1. In this chapter, we defer in our language use to preferences expressed by autistic, Deaf, and blind self-advocates for identity-first language over person-first language (Sinclair, 2013; see also Gernsbacher, 2017; Liebowitz, 2015). The term Deaf with a capital D is commonly used to denote the sociocultural identity. We recognize that language use is varied and evolving and invite commentary on language that best honors individuals and their experiences.

2. The Balance Number Line is part of a larger project, Balance Board Math, that targets a range of different mathematical concepts.

3. The labels of sensory processing disorder and sensory modulation disorder are used in some contexts to describe individuals for whom the sensory features of everyday environments cause frequent difficulties. These labels can arise together with or separately from learning disabilities, ADHD, and autism. Within these diagnostic categories, there are heterogeneous sensory profiles. Rather than a specific diagnosis, the Balance Number Line was developed with an eye toward specifically accommodating individual differences in vestibular sensory sensitivity.

4. A classifier is a handshape that represents a specific thing/noun within the context of a larger sign. For example, a classifier might be combined with a movement representing an action of the "thing" (e.g., a car driving or a person going around a corner), or be integrated into a spatial representation. For example, the number classifier can be used in a sign for "improper fraction" as referring successively to a numerator and denominator in relation to a fraction bar, with the distance between index and thumb larger for the numerator than for the denominator (Kurz & Pagliaro, 2020, pp. 89–90).

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14

Immersive Learning Experiences in Augmented Reality (AR): Visualizing and Interacting with Magnetic Fields

Rebecca Vieyra and Chrystian Vieyra

Recent advances in technology can transform modern, everyday mobile devices into tools to help learners embody and visualize abstract concepts. In particular, the physical sciences can benefit from these learning tools as they pertain to the difficult-to-grasp concept of three-dimensional fields. This chapter presents an exploratory investigation in which multiple learners were provided a sensor-based augmented reality (AR)-enabled smartphone app to immerse themselves in the magnetic fields that surround them. In turn, our observations of learners allowed us to reflect upon the opportunities and challenges inherent to enhanced reality—namely, the "sense of presence" and "the embodied affordances of gesture and manipulation in the 3rd dimension" (Johnson-Glenberg, 2018, 1). Unlike prior work, which has primarily focused on computer-generated field models, this AR experience allows learners to interact with authentic measurements of the Earth's background magnetic field, as well as fields generated by permanent magnets and current-carrying wires. We provide preliminary evidence for how educators can use AR to help users interact with fields from multiple perspectives and build physical intuition for field strength and direction. This chapter will help education researchers and teacher educators to understand the benefits of this embodied kinesthetic approach over more traditional instructional strategies such as the use of two-dimensional diagrams or nonimmersive computer simulations.

Theories of embodied cognition encourage educators and educational researchers to consider not only the internal workings of the mind, but to account for the role of the whole body and the environment for encoding and storing information (Barsalou, 1999; Wilson, 2002, Glenberg et al., 2013). In this vein, the boundaries of the mind extend beyond the physical limits of the brain to include physiological stimuli and perception from other parts of the body, including movement, physical memory, and the way in which people arrange and interpret their surroundings.

Enhanced reality—augmented, virtual, and extended (AR, VR, and XR)—developers can design virtual interfaces and overlays that increase the meaningfulness of gesture and physical space in a way that is oriented toward a specific type of learning, including science (Johnson-Glenberg, 2017; Johnson-Glenberg & Megowan-Romanowicz, 2017; Lindgren & Johnson-Glenberg, 2013). For example, students might look at the world through a camera screen as they jump up and down while simultaneously observing a graph or vector overlay that displays the net force corresponding to their body's accelerations. Making multimodal connections between physical sensations and mental expectations—particularly if the prediction and outcome are discrepant—can be a powerful pedagogical tool because of the way that movement and sensation contribute to memory retention (Broaders et al., 2007; Goldin-Meadow, 2011), a phenomenon called *gesture-enhancing-the-memory trace* (Craik and Lockhart, 1971; Goldin-Meadows, 2014).

Despite the promise of embodiment, educators must use extra care when incorporating new movement-based technology in pedagogical practices in science classrooms and other learning environments (Dunleavy et al., 2009). The potential pedagogical benefits of these technologies to gesture and movement include increasing the connection between the physical environment and academic goals through situated learning (Squire & Klopfer, 2007), learning gains (Yoon et al., 2012; Lindgren et al., 2016), increased agency when manipulating virtual objects in three-dimensional space (Johnson-Glenberg, 2018), and improved attitudes toward learning science, including a sense of co-presence with other participants (Minocha et al., 2017). However, researchers have also expressed concern that enhanced reality experiences that rely on movement input from only one individual at a time can promote more individualized engagement at the expense of collaborative learning that might have otherwise occurred with nonembodied or technology-free activities (Anderson & Wall, 2015).

Physical manipulations are especially important to scaffolding learning (Hostetter & Alibali, 2008), particularly as students in science often have deeply held—and naïve—beliefs about physics (Reiner, et al., 2001), some of which are related to embodied experiences. As a fundamental science, physics explores the properties of mass and energy—concepts that people begin to explore from the moment of their birth through physical interaction with the world. Secondary-level students are usually first formally exposed to physics through an exploration of motion and forces. Although the traditional treatment of physics in many classrooms is grounded in algebraic formulas and word problems, progressive teachers root themselves in practices that exemplify interaction that supports conceptual modeling, including digital simulations as well as physical manipulatives. In addition to the need for intentionally incorporating movement into learning activities, there is evidence that the way physics students gesture as they express their ideas supports their thinking (Chase, 2013).

Burgeoning research in educational psychology suggests that truly effective teachers need to be attentive to students' whole-body learning experiences, especially for addressing beliefs that run counter to fundamental physical principles that are based on *ideal* systems, including forces and motion (Enyedy et al., 2012; Vieyra, 2018) and waves (Wittman & Chase, 2012), or ideas that are highly abstract, such as energy (Close & Scherr, 2015; Dreyfus et al., 2015) and electromagnetic fields (Buchaeu et al., 2009; Johnson-Glenberg & Megowan-Romanowicz, 2017). More generally, Weisberg and Newcombe (2017) describe the potential for embodiment to help bridge thinking toward abstraction by building embodied analogies for abstract concepts, promoting nonverbal gestures that can help express ideas, encouraging the use of new strategies for thinking, off-loading cognition to the physical world and other scaffolds, and using visual representations.

Embodiment is especially important for understanding the concept of fields. Fields are the physical spaces in which every day fundamental forces operate, such as gravity, electricity, and magnetism. Students' conceptualizations of fields are an essential yet often overlooked foundational concept in the physical sciences. In the *Framework for K-12 Science Education,* US leaders in science, technology, engineering, and mathematics (STEM) and STEM education recognized the importance of the inclusion of fields as an underlying disciplinary core idea that all children should learn for general science literacy (NRC, 2012) as well as for their advanced technical applications (NRC, 2013). Being able to visualize magnetic fields is important for understanding experiences as commonplace as transmitting radio signals to a car stereo system, or as cutting-edge as doing atomic particle research.

Reviews of physics education research demonstrate that researchers have historically heavily focused on students' conceptualizations of one- or two-dimensional motion, forces, energy, and electromagnetism (McDermott & Redish, 1999), as earlier physics education researchers were typically physicists by training. More recently, however, physics education research has expanded to include cognitive processes—how these conceptualizations are formed over time (Docktor & Mestre, 2014). Between these two reviews, only one research-based initiative, SCALE-UP (Beichner et al., 2007), explicitly incorporated three-dimensional field representations.

Our work addresses in greater detail how learners move toward robust conceptualizations of three-dimensional fields and how they do so with the support of embodied AR experiences. In the remainder of this chapter, we present a brief overview of the concept of fields, describe a sensor-based AR mobile app that we designed for students, and reflect on our initial findings about the affordances of AR for teaching and learning.

A Brief Primer on Fields

Scientists conceptualize fields as infinite spaces that are caused by an energy source, such as matter (in the case of gravity), a charged particle (in the case of electricity), or a set of magnetic poles (in the case of magnetism). They typically represent their conceptualization of fields with field vectors (figure 14.1), which show the relative strength and direction of the field at a given point. In the case of magnetism, fields are defined as pointing from north to south poles, and they increase in length as the field gets stronger near the poles. This visualization can be quite simple for uniform sources, such as a bar magnet when represented in two dimensions, but quite complex when more than one source is involved or when considered three-dimensionally.

One of the major challenges with the study of fields is that they are abstract because they are both invisible and intangible. Even until Einstein's publication of *The Evolution of Physics* (Einstein & Infeld, 1938), the concept of fields was not widely accepted by the general population. Fields are largely unrecognized

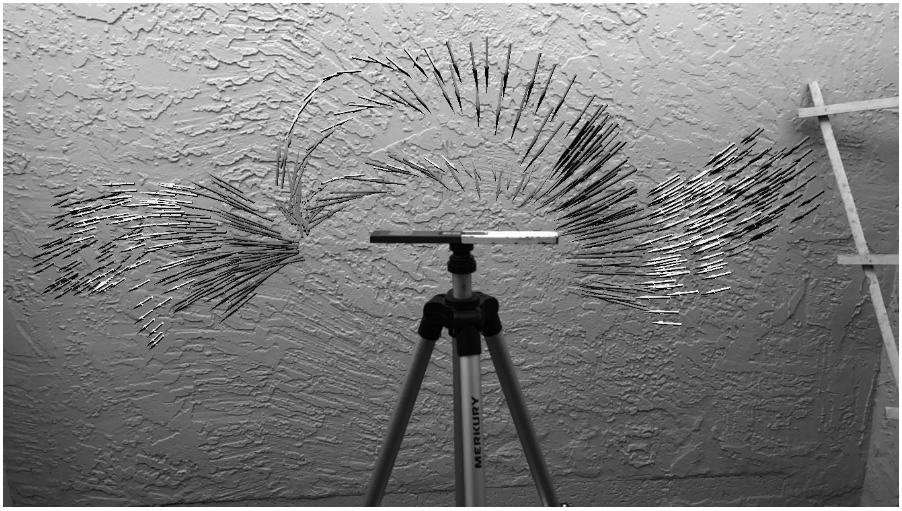


Figure 14.1
Field vectors around a bar magnet, as visualized through the Magna-AR app, the smartphone app developed by the authors and their team. Credit: Don Balanzat.

because they can only be deduced from evidence of their interaction, such as the force felt by two magnets as opposing poles attract or similar poles repel.

Despite their importance, fields are very poorly understood by students. Maloney et al. (2001) developed an assessment for incoming undergraduate students that focused on magnetic force, magnetic field caused by a current, and magnetic field superposition. They found that student scores were no better than random choice, suggesting that even if students had any exposure to the study of fields in high school, little to nothing was retained by the time they entered the university. Ding et al. (2006) documented the relatively low level of student understanding of electrical and magnetic fields even among physics and engineering majors who had taken introductory college coursework. Collectively, these studies demonstrate that traditional instruction does a poor job at helping students to understand magnetic fields. Li and Singh (2011) also noted differences in performance in understanding about magnetic fields by gender, with males significantly outperforming females on assessments of growth. Therefore, the traditional ways of teaching about fields might disadvantage women, who are already underrepresented in the physical sciences and engineering.

There have been multiple efforts to measure students' understanding about magnetism (Ding et al., 2006; Maloney et al., 2001; Marx, 1998), but the majority of these assessments look at electromagnetic relationships—often based on formulaic relationships—with little regard for hard-to-grasp fields as their theoretical basis. On all of these aforementioned assessments, very few questions address the three-dimensional nature of fields, and none explore irregularly shaped fields or the nature of the Earth's magnetic field.

Both because teachers themselves might not be comfortable with fields, and physics education research has yet to reveal student thinking about foundational field concepts, it can be easy for teachers to gloss over the topic, thereby maintaining subpar pedagogical approaches. For example, Greca and Moreira (1997) found that most students were dependent on "propositional" understandings of magnetic fields and analytic problems, and struggled with more conceptual problems. They hypothesized that these trends exist because traditional physics instruction emphasizes rote problem solving rather than rich conceptualization.

In addition to being invisible and intangible, a second major challenge in teaching students about fields is that they are three-dimensional. Literature suggests that students often need support to develop visuospatial awareness for three-dimensional science concepts (Stieff et al., 2005), which includes fields in physics. The extent of most students' exposure to magnetic fields, specifically, is observing iron filings align on a paper placed on top of a bar magnet (figure 14.2), or observing iron filings suspended in oil as they display a uniform

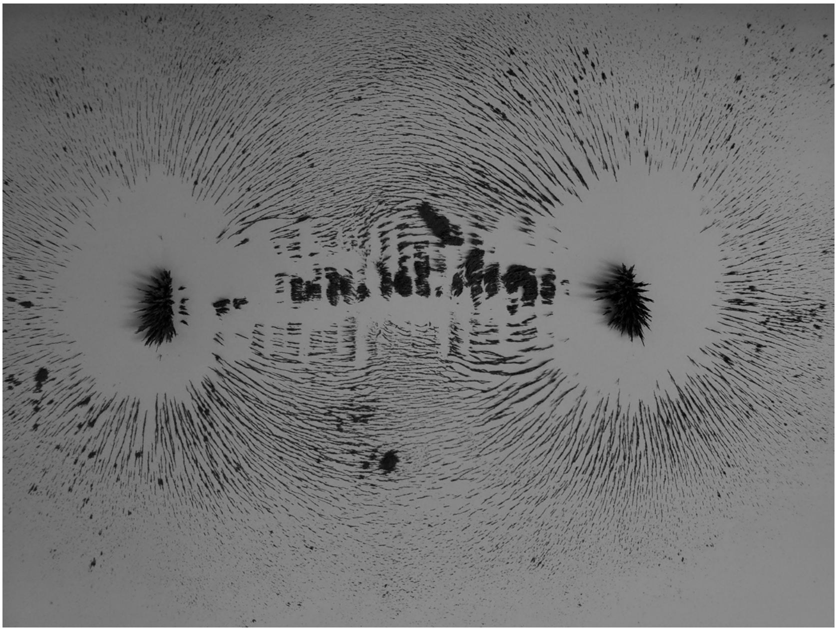


Figure 14.2
Iron filings sprinkled onto a piece of paper resting on top of a stack of button magnets.

field around a cow magnet. A more creative teacher might also set some gelatin with suspended iron filings around a magnet, allowing students to see three-dimensionality by slicing cross-sectional layers for them to observe.

Understanding the three-dimensional nature of magnetic fields requires high-level visualization and spatial reasoning skills, particularly as they are not always static—magnetic fields can be produced by permanent magnets and electric currents (electromagnets) alike, and they can interact with one another when there is more than one source. One study of student understanding involved eight physics majors (López & Hamed, 2004). When given a two-dimensional printed image of a system that included electric currents, students were unable to accurately describe the three-dimensional magnetic fields produced by the system, even though all the students demonstrated a clear understanding of the underlying physics of the relationship of magnetic field and current (the Biot-Savart law). When viewing the current system as a three-dimensional computer visualization that could be manipulated with rotation and zooming capabilities, however, all the students were able to correctly describe the fields. An analysis of students' interviews demonstrated that the manipulation of the spatial information through two-dimensional mental images was producing too much cognitive load. The visualizations allowed the students to correctly integrate the spatial information into the physics they understood. The authors concluded that "the use of three-dimensional images could be a very important pedagogical tool in introductory physics courses when students first encounter the subject of magnetic fields and their relationship to electric current" (López & Hamed, 2004, 1517).

Although research on three-dimensional visualization has often relied on computer-generated models superimposed onto a flat screen or perspective drawing on paper, augmented reality (AR) technologies bring the added benefit of movement to learning about magnetic fields. AR has the potential to improve both visuospatial capabilities (Martín-Gutiérrez et al., 2010) and general learning outcomes about magnetic fields and enhanced student-reported interest when compared with traditional instruction (Buchau et al., 2009; Billinghurst & Duenser, 2012; Dori & Belcher, 2005; Ibáñez et al., 2014). For example, Billinghurst & Duenser (2012) developed an AR-supported visualization that allowed users to flip the poles of a magnet and move it around. The AR tool led to greater gains than with traditional instruction. In another example, Ibáñez et al. (2014) used plastic paddles with printed targets to visualize magnetic fields. The students who used the AR tool were more likely to demonstrate cognitive "flow" in the learning process compared with their classmates who received traditional instruction. Finally, Scheucher et al. (2009) took a slightly different approach in which they created a simulated world that visually modeled three-dimensional fields on a computer screen based upon students' physical manipulation of laboratory equipment. These particular experiences, however, were limited in that movement and gesture were minimized (i.e., restricted to digitally rotating objects, and to computer-generated theoretical data with no opportunity for the exploration of irregular fields).

A number of prior studies have involved movement and gesture, but none of them have explicitly studied the implications or the role in learning about magnetic fields. In the following section, we describe how we developed a novel smartphone-based AR tool that is different from prior studies in two important ways: (1) it uses a handheld visualization interface that encourages learners to use their hands and bodies to guide exploration in the wide environmental spaces around them and does not limit them to a laboratory table or computer screen in a synthetic environment, and (2) it displays authentic data captured by the internal magnetometer, thereby encouraging learners to consider the importance of their own gestures for creating meaningful field visualizations.

An Embodied Solution: Magna-AR

To address the difficulties with teaching and learning about three-dimensional fields, developers, educators, and researchers (Vieyra Software, the American Modeling Teachers Association, and Embodied Games) developed a smartphone-based, handheld AR experience for visualizing magnetic fields. In 2018, the team received funding from the National Science Foundation to pursue a project to develop the mobile sensor-based app Magna-AR (see www.magna-ar.net). Magna-AR makes use of recently developed software frameworks in modern smartphones, including Apple's ARKit (https://developer.apple.com/arkit) and Google's ARCore (https://developers.google.com/ar/discover/concepts).[1] By combining the power of the smartphone's internal magnetic field sensor, accelerometer, gyroscope, and visual cues through the camera, the app has a sense of spatial awareness and can superimpose magnetic field vectors in real space.

To build the app, we drew on our experiences with the development of Physics Toolbox Play (Vieyra et al., 2020), a specialized app funded by the American Physical Society for educational outreach.[2] In observing users interact with the app, we realized how much movement the challenges required as well as how much movement the raw data visualizations seemed to inspire (figure 14.3). For example, we routinely observed students run up and down stairs to observe changes in air pressure on the barometer reading, spin in chairs to observe changes in g-force on the accelerometer reading, and struggle to rotate the phone in the appropriate orientations.

To promote movement, Magna-AR was designed so that users must tap the screen to measure the magnetic field at various locations throughout space. Each tap places a magnetic field vector at the point of measurement, creating a collection of arrows that appear to float in space around the object. The user can move, viewing these arrows from different perspectives (figure 14.4). Moving away from a magnetic field source, while continuing to place vectors, will reveal the Earth's background magnetic field. Tapping the screen while moving around a strong permanent magnet will reveal a set (or sets) of poles, while moving around an object like a direct current-carrying wire will reveal a circular pattern.

Initial Observations of Gesture to Understand Magnetic Field Conceptualization

Our observations of new users of the app reveal that they usually perform a number of gestures suggestive both of their naivety with fields and with three-dimensional visualization. As users became more comfortable with the

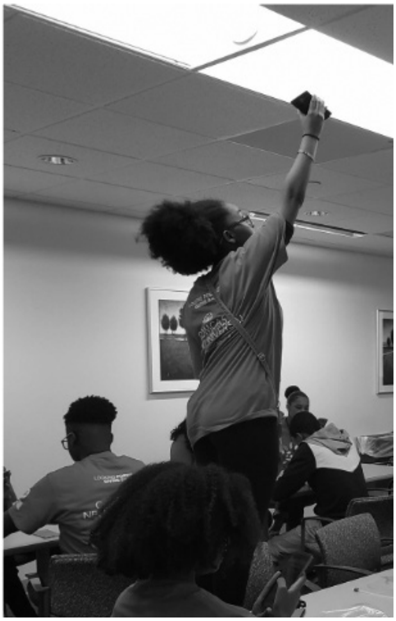


Figure 14.3
A high school student stands on top of a chair to complete a data-verified physics challenge using Physics Toolbox Play.

app and the concept of magnetic fields, they built up a repertoire of gestures that help them to make sense of complex data and allow them to more strategically explore scenarios. In this section, we explore some of the movements that we see users make, and hypothesize both what these movements reveal about thinking and how we might design activities to challenge naïve ideas about fields and their visualization while supporting their learning progression.

We have used the app informally with multiple individuals and groups, including adult physicists, science educators, and undergraduate students. Initially, we used a loose protocol to observe users' struggles with using the app and natural tendencies in how they explored its features. We began by describing to the user how the app places a vector representing the magnetic field strength and direction at the general location of the smartphone's magnetometer when the screen is tapped. We then encouraged users to explore the space around them while narrating their observations and questions. To motivate them to explore both their natural environment and permanent magnets, we provided users with ten to fifteen button magnets that could be stacked together to serve as a bar magnet or separated and arranged on a table.

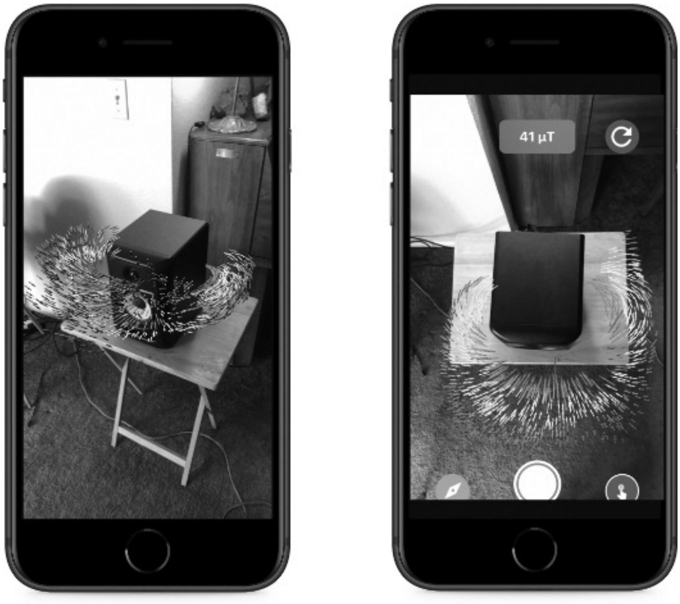


Figure 14.4
Magnetic field vectors displayed around the strong permanent magnet of a stereo speaker, shown from side and top perspectives. Credit: Don Balanzat.

Regardless of professional expertise in physics or familiarity with digital devices, we found that users demonstrated a variety of initial gestures in phases. These phases included (1) an initial hesitation to translate their bodies and motions that suggested a naïve idea about how visualizations are produced, (2) an overestimation of the range of detectable fields from a magnetic source as well as surprise at the immersiveness of the Earth's background field, and finally (3) a period of accommodation in which users find physical and logical boundaries in order to produce visualizations that make sense to them.

1. Hesitation to Translate Undergirded by a Reliance on Emission Theory

We expected that our app's visualization capabilities would naturally encourage users to move and explore their environment. However, we were surprised that users hesitated to translate (shift the position of) their bodies or their handheld smartphones from their initial position. They frequently changed perspective by angling the phone while maintaining their position and placing vectors, as in "looking around" from a single point, but they rarely stepped away from their starting point unless encouraged to do so.

Some of the hesitation to translate was likely the result of users not being familiar with a tool that can only visualize fields that have been sensed by being placed at various points in space. Based on interviews, we know that they expected to be able to see a field within the viewscreen of the phone, even if the phone was not and had never been within the space they expected to visualize. Even scientific experts discussed their expectation to be able to see changing magnetic fields, such as those produced by a wire with alternating current, despite the fact that it is logistically impossible to capture the magnetic field across multiple points at the same moment in time.

We hypothesize that this self-imposed constraint on whole-body movement and gesture suggests that users are applying the emission theory (Winer et al., 2002) to the camera of the smartphone. Emission theory is akin to the kind of "X-ray vision" popularly displayed in comics, whereby beams emanate from superheroes' eyes to visualize objects in front of them. Winer at al. (2002) found that over half of all adults ascribe to the belief that light emanates from our eyes, even after traditional instruction on the inaccuracy of the theory. Winer noted that this persistent misconception has been documented since the times of Plato, so it is not surprising that people might apply it to the camera (the "eye") of a smartphone even in modern times.

2. Overestimation of Measurable Field Distances and Surprise at the Nature of Immersive Fields

Another tendency we observed was for users to attempt to visualize the fields of permanent magnets while a significant distance away—often on the order of half a meter or more. The first response from users was often surprise at the fact that they were able to observe a uniform field all around them wherever they collected data, rather than only a localized change caused by the permanent magnet, as they expected. They were also surprised that the uniform field pointed north with a downward angle, not parallel to the ground.

Users usually needed coaching to get closer to the permanent magnet in order to see a field pattern similar to what they might have experienced previously with iron filings (figure 14.5). We recognized that the typical starting distance for visualization might be a combination of the adoption of the emission theory, the tendency to be a certain distance away from the subject when taking photos and videos during normal smartphone use, as well as a fear of magnets damaging their smartphone (many users expressed this as their first fear when we present them with magnets).

We also hypothesized that these gestures suggest that users do not have a strong grasp of the relative magnetic field strength of permanent magnets to each other or to the Earth's background field. This observation was significant, considering the fact that most people have played with magnets and realize that a magnetic force cannot be felt between two magnets until they are within a few

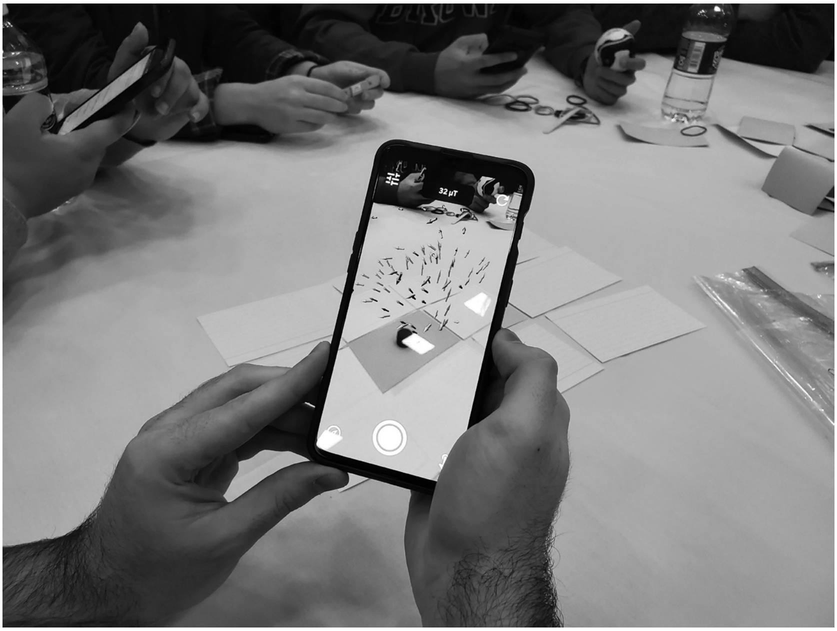


Figure 14.5
An undergraduate physics student plots the field around a small stack of magnets.

centimeters of each other. The strength of a dipole magnetic field decreases by the inverse cube of the distance from it, meaning that doubling the distance from a magnetic source decreases by eight times, a principle that can be easily verified with a smartphone magnetometer (Arribas et al., 2015). As a result, one could not reasonably expect to sense an appreciable field of a small magnet at such a distance, especially in comparison to the relatively strong terrestrial field.

Initially failing to see any perturbation in the field from the permanent magnet, users' attention was often drawn to the environmental field caused by the Earth, resulting in a two-dimensional exploration of the field. Most users eventually acknowledged the reasonableness of seeing the Earth's background magnetic field, but many noted their surprise at its downward orientation of this field (figure 14.6). In Washington, DC, for example, the Earth's magnetic field dip angle is approximately sixty-five degrees below the horizontal (NOAA, 2019). Users' lack of awareness of the dip angle—even among seasoned physicists—is not unusual, even though physicists often conveyed after that they knew that the dip angle can be measured without AR tools, using either a specialized vertical compass or the graphical or digital readout of a smartphone's magnetometer (Arabasi & Al-Taani, 2016). Regardless, it is clear

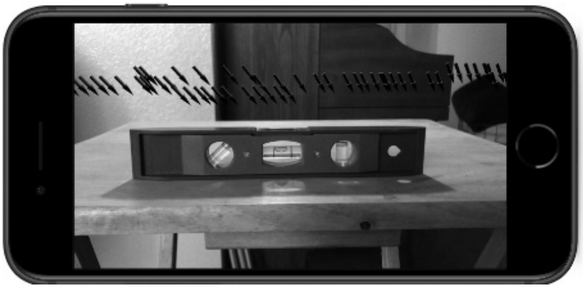


Figure 14.6
A strip of vectors displaying the dip angle of the Earth's background magnetic field. Credit: Don Balanzat.

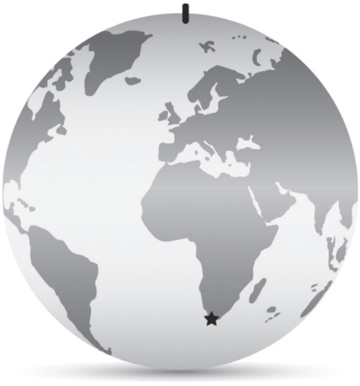
that most individuals use an implicit flat-Earth worldview when they think about the Earth's magnetic field.

The surprise associated with users' exploration of the Earth's background magnetic field suggested that they likely associated the four cardinal directions with a flat plane tangent to their point on the Earth's surface, rather than the more curvilinear field lines that emanate from the Earth's magnetic poles. Through the use of questions on a concept assessment we developed, the Magnetic General kNowledge Assessment (see figure 14.7), we also noted that users had little sense of how perspective shifts at various points of the globe, as would be consistent with numerous studies in astronomy education research (see the review by Cole et al., 2018) and in psychology (Vandenburg & Kuse, 1978). We also anticipated that few users have ever noticed that the needles in mechanical compasses are tilted when held on a level surface.

3. Exploring Physical and Logistical Boundary Conditions and Making Sense of Fields

As users became comfortable with the app, they began to explore the physical limitations for meaningful field visualization around magnetic field sources. Users learned to balance distance from the magnetic field source (too far, too close), vector density (too many, too few), and positionality (sweeping uniformly, focusing on points of interest).

During the mapping process, we found that users developed a spatial awareness of the range of measurability and influence of the permanent magnet. Once users realized that vectors can only be placed when the smartphone sensor is located at the point of desired measurement, they began to experiment by getting close to the magnet, which typically led to some frustration. When the magnetometer got too close to a magnet, it became saturated and needed recalibration before being able to collect additional data. Recalibration required its own special gesture, a



When standing at the star's location, which way does the magnetic field sensor's arrow point?

a. Toward Earth's north geographic pole and *downward* towards the ground

b. Toward Earth's north geographic pole and *upward* towards the sky

c. Toward Earth's north geographic pole and *parallel* to the surface of Earth

d. Toward Earth's south geographic pole and *downward* towards the ground

e. Toward Earth's south geographic pole and *upward* towards the sky

f. I do not know

Figure 14.7
A question that assesses learners' understanding of global perspectives of terrestrial magnetism.

three-dimensional figure eight, to reset the magnetometer readings. Getting too close also decreased the number of available visual cues for the smartphone camera that were necessary for anchoring measurements in real space. Losing visual cues also led to a loss of frame of reference and caused previously recorded sensor data to drift, making meaningful visualizations especially difficult. Getting too far from the permanent magnet led not to an empty field but a view of the Earth's background field, which obscured the field of interest.

We then noted that users began to explore more carefully, shifting the speed and uniformity of their movements as they increased attention to the right number and density of vectors to see patterns, as well as the right amount of data collection in points of interest, such as the extreme ends of the magnet. We believed that as users' maneuvers became more precise, they were becoming more attuned to what was important in the visualization. At this point, many users began to explore fields of their own creation, such as laying out an array of button magnets with the same or alternating poles pointing upward, or seeking magnetic perturbations caused by magnets in their environment.

Discussion and Conclusion

The embodied learning approach to exploring magnetic fields with a sensor-based AR-enabled smartphone app both illustrates the affordances of whole-body learning experiences and displays the importance of attending to AR experience design. Our preliminary findings are situated within embodied research for gesture and three-dimensional immersion. For example, studies have proposed degrees of embodiment based on three constructs: (1) the amount of sensorimotor engagement, (2) the congruency of the gestures to the concepts to be learned, and (3) the amount of immersion experienced by the user (Johnson-Glenberg et al., 2014; Johnson-Glenberg & Megowan-Romanowicz, 2017; Johnson-Glenberg, 2018). Within this framework, we have identified three preliminary findings.

First, we realized in the case of fields that naïve ideas about physics (i.e., emission theory) and about how smartphone sensors collect and visualize AR data inhibited users from freely exploring their physical space without our explicit encouragement. In our case, users did not initially link movement to place-anchored data collection, such as is necessary in sensor-based AR experiences—in effect, movement-based exploration might not come naturally to all learners, limiting the sensorimotor engagement of users with the experience. As a result, considerations about prior conceptual knowledge are essential for effectively applying more discipline-agnostic design principles for mobile AR (Li & Duh, 2013) and assessments of the quality of immersive experiences (Johnson-Glenberg, 2018).

Second, even experienced physicists acknowledged surprise at the nature of the magnetic fields in which they were immersed. Many of them admitted to theoretically knowing what Earth's background magnetic field or that of a permanent magnet "should" look like, but only upon moving through it and visualizing it were they able to reconcile their instinctual response with their theoretical knowledge. This sense of Earth's regional appearance of flatness is motorically embodied in our minds, as are our perceptions of three-dimensional objects in general (Makransky & Peterson, 2021). With the difficulties of unrooting such ideas to better account for shifts in perspective, this finding emphasizes the high potential of embodied AR experiences to make improvements over traditional educational approaches by embracing a deep sense of immersion that forces users to address discrepant expectations and realities.

Third, with time and experience, users become more precise in their movements to make sense of the data that they were collecting to covisualize the data with the app. Based on feedback from the app (such as sensory overload) and the oversaturation or undersaturation of visualized data, users were able to self-regulate how they explored their environment in a way that demanded congruency of gesture not so much as an app-design limitation but as a physical limitation imposed by the magnetic fields themselves.

Our application, Magna-AR, is one of a limited number of examples of how smartphones can use sensor-based data paired with AR to see invisible magnetic fields by allowing the user to be the co-creator of the visualizations by moving their body in space. We recognize that there are a wide variety of commercial resources for enhanced reality, including wearables and cameras that track and mirror the movement of hands and limbs. However, we anticipate that the use of authentic data visualization tools held at arm's length from a first-person perspective, such as smartphones, can provide alternative benefits over technologies that anchor perspective to the head or playing field, or that provide only computer-generated scenarios.

Although our work focuses on a topic within physics education, we hope that the examples we provide draw attention to the importance of movement-based learning and assessment in general. Specifically, we encourage educators and educational researchers who rely on written and oral assessments to additionally consider how gestures can support understanding and reveal learners' struggles and understandings. Additionally, we intend for our work to showcase the potential for handheld AR technology for three-dimensional visualization that is already accessible to a large population of educators and learners through their smartphones. Ultimately, we hope that tools such as Magna-AR and the lessons we have learned along the way can provide additional information about learners' first-person-view exploration of concepts in three-dimensional space.

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15

Evaluating Embodied Immersive STEM VR Using the Quality of Education in Virtual Reality Rubric (QUIVRR)

Mina C. Johnson-Glenberg

This is a pivotal time for virtual reality (VR) and education because VR is becoming more affordable and accessible. To that end, all guidelines and rubrics are helpful for both educators and designers. As three-dimensional (3D) immersive VR is becoming more common in educational settings, instructors and designers need procedures and best practices for what works. Learning scientists have a role to play in the development of these educational rubrics. A systematic analysis by Radianti et al. (2020) uncovered several gaps for VR in the higher education space. Among them are the lack of cited learning theories, and the unfortunate fact that most evaluations of educational VR applications have, to date, focused on usability and not on learning outcomes.

Educational designers have traditionally had two models to follow for VR content design. In this chapter, I recommend a third way for this novel technology, one that considers the unique affordances of VR. The first model has traditionally involved taking two-dimensional (2D) content and wrapping it in an immersive 3D "feel." This can often result in a VR lesson based on the same static PowerPoint-style presentation to which we have become accustomed.[1] The second model comes from the entertainment sector and starts with the presupposition that basically any graphically rich content with a strong narrative and high production values will lead to engagement—which then automatically leads to learning.

As more educational content is being ported to, and designed for, multidimensional VR devices, designers should create content that takes advantage of what VR does well, and this requires a reconceptualization beyond how the 2D content was created. Additionally, instructors and educators who are trying to decide which content to purchase need to be savvy consumers. This rubric has been created to serve both audiences—to aid educators in decision-making and to aid content designers by serving as a type of checklist for the activities and constructs that should be present in their VR content. The in-headset activities should take advantage of the affordances offered by the multiple dimensions in VR.

The Affordances of VR

Bailenson (2018) lists his top four uses of VR: when content is impossible in real life, too expensive, too dangerous, or counterproductive (e.g., cutting down a forest to demonstrate the negative effects of deforestation). To those four, we add what have been called the two profound affordances of VR (Johnson-Glenberg, 2019). The first profound affordance is *the sensation of presence,* which designers must learn to support, while not overwhelming learners. Slater and Wilbur (1997) describe presence as the feeling of being there. It is a visceral transportation that, in many individuals, occurs immediately.[2] The second profound affordance pertains to *embodiment and agency associated with manipulating content in 3D.* Manipulating objects in multiple dimensions gives a learner more personal control (agency) over the learning environment. It is qualitatively different than the "click and drag" experience on a 2D personal computer (PC) monitor. A recent study using functional near-infrared spectroscopy (fNIRS) showed differences in hemodynamic activity between a PC game-based learning experience and a VR learning experience (Lamb et al., 2018).

Emerging Use of Term "Embodiment" in Extended Reality

The field has started to use the term extended reality (XR) for the continuum of augmented reality (AR) to mixed reality (MR) to VR. As the latest generation of augmented reality (AR) glasses and VR headsets become more affordable, educational designers are beginning to include more body movement and representational gesture in lessons. Decades of research suggest that gestures and body-based metaphors can benefit learners of many ages (Antle, et al., 2009; Goldin-Meadow, 2011; Johnson-Glenberg, et al., 2016), in many different types of learning situations (formal and informal) (Johnson-Glenberg, et al., 2015; Lindgren, et al., 2016; Yoon & Wang, 2014). One hypothesis is that learners who are engaged in higher levels of embodiment will learn content faster and in a deeper manner because activating sensorimotor codes strengthens memory traces. In addition, gestures may attenuate cognitive load (Goldin-Meadow, 2011, 2014).

The amount of embodiment in any educational game exists along a range. An early taxonomy by Johnson-Glenberg et al. (2016) listed discrete degrees of embodiment in a lesson, but a more recent taxonomy allows for a range along three axes. These can range from low to high (Johnson-Glenberg & Megowan-Romanowicz, 2017, the axes correspond to three embodied constructs: (1) the amount of sensorimotor engagement, (2) the congruency of the gestures to the content to be learned, and (3) the amount of immersion/presence experienced by the user. Note that another, simpler taxonomy exists (Skulmowski & Rey, 2018), which focuses on two dimensions: bodily engagement (i.e., how much bodily activity is involved) and task integration (i.e., whether bodily activities are related to a learning task in a meaningful way or not). The authors hypothesize that being higher in the grid will correspond to better learning outcomes. Because our laboratory/studio (Johnson-Glenberg) creates content with immersive emerging technologies, we maintain that it is important to keep the third axis of presence/immersion in the taxonomy. If bodily engagement is part of a lesson being considered more embodied, then the use of VR head-mounted display (HMD) tracking cameras and hand controllers will allow for more action and gesture to be captured. These gestures (and even fine finger movements) can be used as inputs for interactivity.

We know that embodied gestures positively affect encoding and learning. As an example, in a recent word learning study (Fuhrman et al., 2020), participants studied vocabulary words by either repeating the word, making an “irrelevant” gesture (e.g., two hands making a circle), or functionally manipulating the object (e.g., physically enacting picking up a virtual hat and placing it on one’s head). Participants demonstrated improved comprehension rates for the manipulated objects, suggesting that VR holds “the potential to offer a more authentic, multisensory and motor context to efficient foreign language learning” (p. 15). VR lends itself to the types of kinesthetic interactivity that can provide another multimodal signal for learning.

In the XR community, it is not uncommon for authors to write about embodiment in terms of *how humans inhabit their avatars’ virtual bodies*. As an example, Banakou et al. (2018) use the term “embodied” to mean the player is taking on a new identity that is associated with the avatar (in their case, Einstein). We acknowledge the term embodied in VR can also refer to full body-avatar extension simulations. In sum, there is no right or wrong way to use the term embodied in VR, but we recommend that authors state in the introduction how it is being used.

Authors might also speculate where on the continuum of embodiment their game would land. Embodiment is considered “complex as it includes not only body ownership over the avatar, but also agency, co-location, and external appearance” (Gonzalez-Franco & Peck, 2018). For the purposes of this chapter, the term embodiment is not avatar-dependent: embodiment means that the user is making choices via gesture that affect the action on the screen. In addition, there should also be a congruency with (that is, a match to) what is being manipulated and the content to be learned.

Evidence for Embodiment and Platform Factors in VR

In the following section, we describe two games and one study that helped in designing this rubric. Johnson-Glenberg et al. (2020; 2021) investigated whether certain learning activities that are well-tolerated on a 2D desktop (PC) platform may become infelicitous for learning when moved to a more immersive VR platform. Learning interactions and types of learning objects that are perceptually well-handled when viewed on a flat screen (i.e., observing videos) may not translate well to 3D VR.

The laboratory created a "medium-high embodied" game called *Catch a Mimic*.[3] The *Mimic* game includes two instances of kinetic embodiment using either the mouse or VR hand controller: (1) swooping the virtual butterfly net (congruent, yet highly repetitive), and (2) manipulating the interactive bar chart (described more in the next section) (see figure 15.1). There were highly

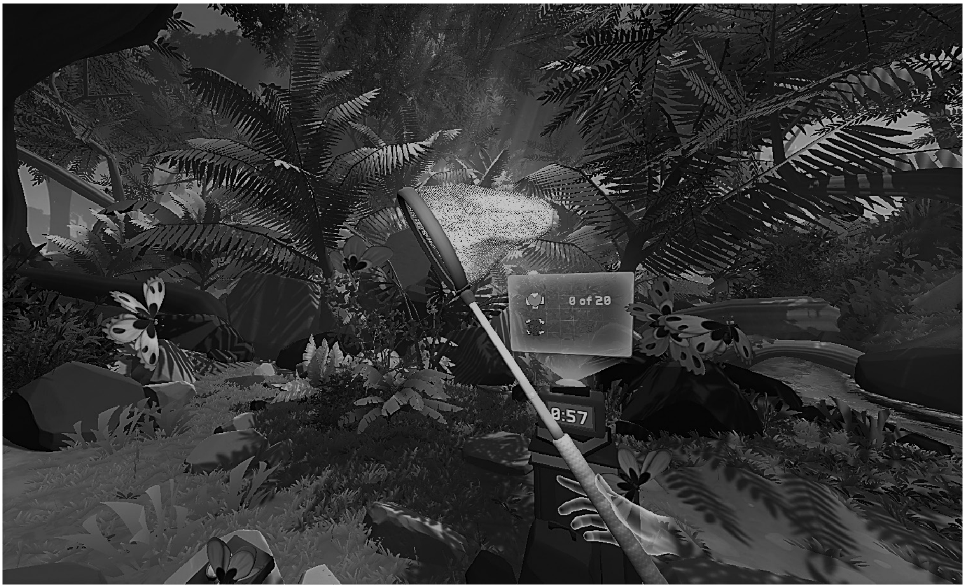

Figure 15.1
Screen capture of the virtual hand and net capturing butterflies. Real-time feedback is displayed in the center screen, and a timer clock appears below that.

embodied components present in the game, but one of them was so repetitive that it brought down the categorization medium-high embodied.

The second educational VR experience that influenced our thinking was a low-medium embodied game called *Titans of Space-Mobile*. The Oculus Go version of *Titan* allows the users to look down and see a seated avatar in a space suit and to control navigation through space with a trigger to visit our solar system's planets and moons. Once a celestial body has been reached, however, there is no manipulation of the celestial body. Rather, players can only click and read text about the celestial body.[4] We invite readers to download either game and fill out the attached rubric, and you can decide on their quality for educational purposes.

The laboratory used the *Catch a Mimic* for a randomized control trial study to determine how two levels of embodiment—low embodiment (limited activity) or high embodiment (more active control over environment)—might affect learning on two different platforms: 2D (PC based, low immersivity) compared with 3D (VR based, high immersivity). Because 3D has consistently been found to be more engaging and immersive than a 2D platform, it would be tempting to believe that everything will be learned better in VR. This may not be the case.

Two hundred and fourteen college students participated in this 2 × 2 between-subjects study. The first factor was embodiment (low versus high), the second factor was platform (or immersivity)—also low versus high. In the low-embodiment level the participants viewed a recorded playback of the game being played by a first-time player. The low-embodied participants had control over the "next" button, navigation, and filling in two instances of an interactive bar chart, but no control over manipulating or swooping the virtual net to capture flying butterflies. In the high-embodiment level, the participants had control over all these aspects of the game. The second factor was platform immersivity: low was PC and high was VR.

The results revealed that the lowest gains in learning about natural selection were exhibited by the low embodied VR group. Content knowledge was assessed with an experimenter-designed pretest-posttest. In addition, we found the highest gains in learning were seen in the 3D VR platform when it was embodied. We suggest that a higher level of embodiment produced better outcomes because those in both of the high-embodied conditions were able to be agentic (either with the mouse or VR hand controller). The significantly lower gains in the low-embodied VR group may have occurred because users had expectations about agency and control, and these expectations probably differed from those in the traditional PC platform. Participants may be accustomed to watching playback screencasts (essentially videos) on a PC, but they have different expectations in an immersive VR environment with a hand controller. Therefore, being passive in an immersive environment, where agency and control are expected, can be deleterious to learning. VR educational designers should not treat the learner like a passive observer. Although videos might work acceptably in 2D environments, they are not optimal in 3D immersive environments.

This finding helped to substantiate the inclusion of active and agentic behaviors in performing assessment of VR learning. The genesis to create the new Quality of Education in Virtual Reality Rubric (QUIVRR) came from the results of that study (Johnson-Glenberg et al., 2020). It was also evident that such a rubric was needed to help fill the VR design guideline void. Additionally, the lack of clear pedagogy in the design of educational applications is considered a problem for the field of VR (Abrams, 2020).

Quality of Education in Virtual Reality Rubric (QUIVRR)

VR is different. So, again, learning interactions and types of learning objects that are perceptually well-handled when viewed on a flat screen (i.e., observing videos) may not translate well to 3D VR. The QUIVRR rubric was created to aid both educators and designers. It is noted here that the avatar section was based, in part, on Gonzalez-Franco and Peck's (2018) thoughtful review of over thirty embodiment experiments that have used questionnaires since 1998. They chose twenty-five of the most indicative questions regarding embodiment in VR and ran a principal-components analysis. They ended up with six question "types" for embodiment of avatars (Gonzalez-Franco & Peck, 2018, p. 3). Our proposed QUIVRR rubric addresses types 1, 2, 3, and 5. The original six are

1. *Body ownership.* Present whenever there is a substitute body or body part.
2. *Agency and motor control of the body.* Present whenever there is motion tracking and the participant can move parts or all of the virtual body.
3. *Tactile sensations.* Present whenever there is tactile or haptic stimulation to enhance the embodiment illusion.
4. *Location of the body.* Present whenever there is a substitute body or body part that is either collocated or not collocated with the participant. Participants must feel that their body is in the same location as the virtual body in order to experience an embodiment illusion.
5. *External appearance.* Present when the self-avatar is a lookalike avatar or as control questions when there are shape, gender, race, clothing, or other visual modifications different from the self.

6. *Response to external stimuli.* In many occasions during the experiment there is an event that modifies or threatens the body or body parts of the self-avatar.

Our Rubric

The next section gives an in-depth description of each item in the QUIVRR rubric. Scores can range from 0 to 5. QUIVRR is weighted toward the embodied and active experience (i.e., more points are awarded when the content is designed to use hand controls and includes multiple instances of well-designed body-based metaphors for learning). This is because we do not have a section for empathy induction or heightened emotionality; those constructs are tightly associated immersive VR, but they are perhaps more related to the humanities (e.g., in rhetoric or in storytelling contexts). In any case, points could be awarded for empathy induction for item 20. QUIVRR is broken into three sections: (1) pedagogy/content, (2) mechanics, and (3) bonus items. The first fifty points relate to pedagogy and content, whereas the final fifty points relate to mechanics. At the end, there are additional points for "bonus" scoring; it is unlikely a module will ever score the maximum of 110 points. After each item, an example is listed to help users understand the Likert scale.

1. *Learning goals.* The stated learning outcome goals can be embedded in the beginning of the module. The term "module" here means what is experienced inside the HMD. It is wise to minimize text in a headset, so the learning goals could also reside in a separate document not viewed in the HMD. The goals need to be accessible and attainable, and the learner should be exposed to the goals before the module begins for priming. The module should align well with the learning objectives and critical thinking standards. Ideally, the goals would include higher levels of Bloom's revised taxonomy. The lower levels of Bloom's are remembering, understanding, and applying; the higher levels are analyzing, evaluating, and creating.

Example: 0 = no stated goals; 1 = goals incomplete, only listed at end, only lower level; 3 = goals adequate, but mainly middle level; and 5 = goals clear, easy to access, and address higher level critical thinking. (User always has the option to enter a 2 or 4 as well throughout the rubric.)

2. *Content suited to immersive VR.* These points can be allotted based on the two profound affordances of VR (highlighted previously; see Johnson-Glenberg, 2018) or based on several other criteria from other VR researchers (e.g., see Dalgarno & Lee, 2010, or Bailenson, 2018). (1) *presence*—does the module do a good job of eliciting presence and transporting the learner in a way that focuses attention and affirms the learning? and (2) *agentic manipulation*

using three dimensions. Some good examples of using the spatial realm in VR and manipulation in 3D are protein folding and manipulating vectors of the Earth's magnetic field over space and time.

Example: 0 = content could be learned just as well in 2D; 1 = content is suited to VR, but design does not take advantage (i.e., most artwork is 2D, fairly static); 3 = content is well-suited, and the module makes adequate use of 3D and presence; 5 = content is well-suited and takes full advantage of VR's many affordances including presence and manipulation in 3D.

3. *Technology moving the content toward transformative learning?* There is a marriage of product (the new technology) and process (the new way of learning). We use the substitution, augmented, modified, or redefined (SAMR) model (Hamilton et al., 2016) for technology to clarify levels. At the *substitution* level, the technology makes no difference from the old 2D method of learning. At the *augmented* level the technology is "adding something new but not transformative"; an example would be instead of a teacher reading a story out loud now students use a tablet to both listen and read the text. At the higher *modification* level, technology integration involves a meaningful modification in learning or assessment. An example might be instead of having a student pick a multiple choice answer regarding the concept of acceleration, a student could move a finger across a large tablet to show comprehension of acceleration in an embodied manner that the technology facilitates (see Johnson-Glenberg & Megowan-Romanowicz, 2017). At the highest level, *redefinition,* learning is transformed into a new novel task, into something previously inconceivable. An example might be a colocated MR lesson where teams of students use handheld trackers to manipulate the frequency of light waves and alter the projected, digitized colors on the floor (for examples of transformative MR lessons, see SMALLab Learning).[5]

Example: 0 = no real technological modification, merely serves as a substitute; 1 = low level of augmentation and/or low level of modification; 3 = moderate level of modification; 5 = high level of redefinition for learning, this experience could only happen in immersive 3D VR.

4. *Scaffolding.* This means that the module systematically builds up to the more complex concepts over time. The designers have added more complex components at an appropriate learning pace. As an example, in a virtual biology laboratory, learners might first view a complicated simulation, and later they are able to begin manipulating and exploring the dynamic system (Hossain et al., 2017). Another route involves in-process (real-time) assessing: as learners show mastery of one concept, a new concept is added. The module

should display some evidence of leveling up in difficulty with time or mastery, which is related to Kolb's (2017) Triple E Framework (engage, enhance, and extend) for learning with technology.

Example: 0 = none; 1 = some leveling up of difficulty, but too many variables at once; 3 = attempts to level and scaffold, but not well paced/designed at times; 5 = appropriate, well-paced, and helpful scaffolding.

5. *Quality of active learning.* Active learning means learners are actively making choices in the module and kinesthetically moving their bodies to engage with content (beyond moving the eyes). It implies users have agency. For example, in a MR astronomy simulation, learners run to show the path of a meteor (Lindgren et al., 2016); that is high quality but limited in occurrence (see the mechanics question later for quantity). You may adhere to a more traditional "generative" definition of the term active and constructive learning. A meta-analysis by Freeman et al. (2014) showed that students in STEM classes with traditional lecturing were 1.5 times more likely to fail than active-learning students.

Example: 0 = primarily passive presentations of content, 1 = very small amount of activity by learner (clicking forward); 3 = some active learning; 5 = high-quality, creative, active learning, with users controlling placement of content.

6. *Actions congruent to the content.* This means the learners' actions map well to the learning of the topic. Not every movement must be isomorphic to real-world movements, but there should be overlap. In the *Catch a Mimic* game, the location and velocity of the virtual butterfly net onscreen mapped tightly to the location and velocity of the VR hand controller. In another example, if the learning goal is to construct an entire car engine in a short time and picking a properly sized screw is important, it may not be so critical that the learner spends several minutes twisting the hand controller to simulate screw turning (see lesson 3, number 4, in Schell, 2015).

Example: 0 = no instances; 1 = few instances of congruency and of low quality; 2 = several instances and of fair quality; 3 = a fair amount of congruency, and the actions further a learning goal; 5 = multiple instances of congruency that are creative and further several learning goals.

7. *Guided exploration.* In educational games/simulations it is appropriate to allow for some discovery and free exploration early in the game, but it is important that *eventually* learners receive cognitive and perceptual navigational guidance. Otherwise learners, in STEM especially, tend to create spurious hypotheses (Kirschner et al., 2006). Several methods to guide in multimedia are visual (such as lighting, arrows, and text). Guidance can also be given via audio or haptic cues.

Example: 0 = none; 1 = mainly free exploration; 2 = some guidance; 3 = more guidance but not properly paced; 5 = well-paced and well-designed guidance.

8. *Prompts for metacognition.* Does the content encourage learners to "think about their thinking"? Is there a space for learners to be reflective? For this item, you may consider "outside the headset" situations. Does the written lesson plan include in-HMD prompts as well as postmodule prompts? An example of an evidence-based metacognition prompt would be asking learners if they want to pause to think through anything, or asking them to pretend they are teaching the idea to another student. This latter question might include asking them to make a prediction (Palincsar & Brown, 1984) about what might happen next or to create a question they might ask on a test.

Example: 0 = no prompts; 1 = one prompt, fairly low level; 3 = several prompts of varying levels of quality; 5 = multiple prompts of high quality.

9. *Useful corrective feedback.* Feedback is not simplistic in formative and mediated education (Shute, 2008). When feedback is constant, it can be distracting, especially if it lags too long after the incident. When formative evaluative feedback is included it should not be a simplistic pop-up of "Great try!" after a failure. When feedback is evaluative, it should give meaningful hints as well. A hint box callout could appear with more in-depth information if an incorrect answer has been submitted several times in a row.

Example: 0 = no feedback; 1 = minimum feedback or at the end of module only; 3 = midquality feedback; 5 = useful and actionable feedback with proper pacing.

10. *Assessment included.* Assessment comes in a multitude of forms. When it happens during the experience it is called formative. When feedback happens at end—either in the VR headset or outside—it is called summative. It is possible to embed assessment during learning so that players do not even know they are being assessed. The literature on quality for assessments is extensive; for a crisp summary of quality, see Darling-Hammond et al. (2013), and for an evidence-centered design standpoint, see Mislevy et al. (2012). The test could be old-fashioned paper and pencil one, but it should always be "valid, reliable, and fair." If only simplistic true/false questions are asked, then the module should be scored lower.

Example: 0 = no assessment; 1 = some assessment, but low level; 3 = some assessment both within module (formative or in-process) and at the end; 5 = high-quality assessment that occurs both within module (formative) and at end for summative reflection.

Rubric mechanics

11. *Designed for comfort.* As of this writing (late 2020), all commercial VR headsets force the muscles attached to the lenses in the eyes to fatigue after a while. This effect is also called vergence-accommodation strain. Certain tasks induce this strain faster (e.g., tracking disproportionately sized objects in different planes). Text reading is very straining. Designers should minimize the amount of text, and use a black background with white text. As you quantify comfort and the amount of text in the module, consider the entire length of the module, then consider how much of the visual display is dedicated to reading text or tracking minute objects. Note that having a voice-over with text does not mean players will *not* also read. Just remember less is better.

Example: 0 = too much text/small object tracking leads to eye strain; 3 = a moderate amount of text, and efforts have been made to keep the experience comfortable; 5 = very minimal amount of text, and overall the composition and experience are very comfortable. (Do *not* tally the title or "optional viewable content," such as the credits or answers to hints.)

12. *Reduction of cybersickness.* Cybersickness is polysymptomatic, polygenetic, and affects each individual differently. The Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993) includes three categories: (1) nausea (e.g., stomach awareness and nausea), (2) oculomotor issues (e.g., headache, eyestrain),[6] and (3) disorientation (e.g., vertigo, dizziness, etc. With experience, many of these effects attenuate, and players become habituated. In one study, approximately 50 percent of discomfort was gone by the tenth session (Rebenitsch & Owen, 2016). It is commonly agreed that the negative effects are caused by a visual/vestibular disconnect. Rebenitsch and Owen list several VR design fixes including "partially limiting the degrees of freedom in control when navigating . . . and increased tactile feedback" (p. 122). The ideal speed of avatar navigation is still not known, but cybersickness tends to increase with increasing speed (So et al., 2001). There are known tricks to decrease cybersickness, including using ramps rather than stairs, and making learners more agentic—in control of where they go and with what they interact.

Example: 0 = experience is highly likely to lead to nausea and disorientation (e.g., includes instances of accelerating navigation, excessive yaw axis movement, and little agentic control, such as a roller-coaster); 1 = more than somewhat likely; 3 = may lead to cybersickness over extended time, such as frequent point-of-view changes; 5 = *very unlikely* to lead to nausea and disorientation, providing a large degree of agentic control and nothing should induce vertigo.

13. *How often and how much of the content are manipulable?* Manipulable means *actionable and movable* content in the virtual world; it does *not* include multiple instances where the user merely pushes a button to start a more complex sequence (i.e., push the "T" key for a screw to be turned). Throughout the entire module, how often is the learner encouraged to interact with, or manipulate the content? This item attempts to quantify the instances of "interactive objects" and the frequency of interactivity under user control. Navigation across a room should only be counted as one instance and not counted repeatedly.[7] We agree with Schell's advice: "You are wiser to create a small game with rich object interaction than a big game with weak ones" (2015, lesson 3, point 1).

Example: 0 = no manipulation, only passive viewing; 1 = very low level of manipulable content; 2 = some manipulable content, but few chances to interact; 3 = more instances and more chances, but repetitive; 5 = a high amount of manipulable content and high frequency for interaction, with novel instances throughout.

14. *Avatar creation.* Is there an avatar? Can the learner choose an avatar? How many components of the avatar are customizable? Research in 2D supports that some customization is valuable (Lin et al., 2017). But when users can fully customize their avatars, might there be an inflection point where too much choice leads to wasted time? Additionally, what are the pros and cons of inhabiting nonhuman forms? More research is needed in this domain.[8]

Example: 0 = no avatar; 1 = yes, hands or body present, but no avatar choice—preassigned; 3 = yes, a body and two or three components can be chosen (e.g., clothes, hair, etc.), but only humanoid options; 5 = yes, a body and more than four components are customizable, and nonhuman options are available.

15. *Avatar in play.* Specifically, this item depends on the two dimensions of (1) *amount of avatar displayed,* and (2) *alignment of movements* paired with ease of control (i.e., there is not a complex button sequence to be memorized).

Example: 0 = no avatar, no control; 1 = hand(s) only or poor movement match; 3 = more of the body is shown, and there is adequate movement match; 5 = full body shown and high-quality match (e.g., lips sync well, easy to turn head).

16. *Intuitive interface.* Intuitive means the "the users' unconscious application of pre-existing knowledge leads to effective interactions" (Israel et al., 2009). There should not be a dependence on complicated button sequences for navigation, nor to get questions in the game answered. Actionable items should not be overly spread out throughout the interface (i.e., the learner should never be forced to spin rapidly around in a lesson; see the cybersickness item). Modules and interfaces should be designed with first-time users in mind.

Remember, not all youth are gamers. A percentage of the population also is colorblind, so critical elements and feedback should not rely on red/green distinctions.

Example: 0 = highly cluttered and unnavigable; 1 = somewhat cluttered and not very easy to navigate; 3 = clean interface but not easy to navigate; 5 = clean interface and very easy to navigate.

17. *Sound quality.* Sound in VR elevates all experiences. Nonetheless, a unidirectional tune can play in a loop and become distracting. Even very nuanced, omnidirectional sounds when overused can become overkill. Quality also depends on whether the sound furthers the educational goals. Creative sounds used in feedback count. If the sound is of an extremely low quality or is distracting and irritating, it should be given a reduced rating.

Example: 0 = silent; 1 = low quality and/or poor directional mapping; 3 = acceptable quality and acceptable mapping; 5 = high quality, creative, and synced omnidirectionally.

18. *Haptics/other modalities.* Even though haptics are not yet common in many VR modules, vibrotactile feedback should become more common. Tactile and haptic add-ons are evolving rapidly, they should be included *when they further learning,* and are not distractors.

Example: 0 = only visual; 1 = auditory is included; adequately integrated; 2 = one extra modality, integrated well; 3 = two modalities (beyond audio and visual) are integrated well; 5 = multimodal and very well integrated such that the inclusion creatively furthers learning.

19. *Engagement.* It is possible to hit every line item already discussed yet create an experience that is not engaging or fun. I was once part of a MR lesson that would have scored high on most items, but once in the field it was determined that few high school students could figure out how to walk with a "negative acceleration." Repeated game play led to expressions of frustration. We suspect now that there was inadequate scaffolding in this high school situation—the majority of students did not possess appropriate prior knowledge of the term "acceleration." How do you perform the negative of something you do not understand? But how do you ensure engagement? Should you add a narrative? Several randomized control trials have not supported the simple tenet that more narrative leads to significant multimedia learning gains (Adams et al., 2011; Johnson-Glenberg & Megowan-Romanowicz, 2017). Trust your instincts: engagement (comprised of attention and enjoyment) must be linked with educational payoff and learning goals must be supported.

Example: 0 = not at all engaging (*more broccoli than chocolate*); 1 = somewhat engaging; 3 = engaging; 5 = very engaging and evidences high educational worth. (You may also change any of these scores after you observe users engage with a module.)

20. *Overall quality/other.* This question allows you to make a subjective, multi-item decision. Additionally, you can write-in an item that you feel strongly about, like empathy. If race and gender are not well represented in the module, here is where you can penalize the module and write the reason why in the notes. Some reviewers dislike very low poly artwork; others expect perfect shading. Resolution versus framerate is a constant trade-off in VR; ask if this has been addressed with creativity. Certain elements should result in points deleted. (1) Are there obvious stitch lines? (2) Is the content highly repetitive? (3) Is there obvious aliasing on thin lines? (4) Are the icons uninterpretable? (5) Was very poor judgment shown for physiological comfort (e.g., letters that zoom toward you or the point of view includes flying around without agency, aka, a "magic carpet" effect)?

Example: 0 = very low quality or missed something salient to the reviewer; 1 = some quality was attempted; 3 = good quality; 5 = high overall quality.

Bonuses

The following two items could be worth a total of ten points. However, I have yet to experience a module that would rate 110. The hope is these two constructs will become the norm in the not too distant future and no longer need to be considered bonuses.

- *Adaptive.* Adaptive means that the experience in the module changes according to the learner's performance. The experience is "dynamic" and based on the players' choices made during encoding or one step earlier. Linear pathways cost less money (time) to create compared with dynamic pathways, but we should certainly all be striving for dynamic experiences.

  Example: 0 = no adaptivity; 2 = user control only over a series of predefined, linear pathways; 3= up to three pathways of adaptivity; 5 = four or more pathways that feel seamless, rigorous research has been done to optimize pathway selection. Note: Having the choice over a series of *linear pathways* is only worth 2 to 3 points.

- *Multiuser collaboration.* Collaboration and cooperation are well-researched and well-regarded constructs in education (Johnson & Johnson, 1989). Currently, this item is in the bonus section because it is expensive (more servers and bandwidth) and complex to create multiplayer experiences in VR. We also note there are some negatives associated with collaborative problem solving, including (1) diffusion of responsibility for completing tasks (which affects single student assessments), (2) disagreements that can paralyze progress, and (3) learners getting sidetracked by irrelevant discussions (Graesser et al., 2017). But, in the end, it is probably the case that well-managed social, multiuser content will lead to richer learning experiences that will outweigh the negatives.

Example: 0 = single user only; 1 = a screencast option is included—but only one learner is in the experience; 3 = multiuser for small group only; 5 = multiuser for larger group with synchronous teacher dashboard support.[9]

Conclusion

New and affordable VR systems allow educational designers to include more gesture and body movements into lessons for the classroom. The lack of clear pedagogy in design, including taxonomies for measuring the amount of embodiment for VR educational applications, are considered problems for the field. Therefore, as educational technology rapidly evolves, our design principles and quality rubrics need to keep pace. The QUIVRR rubric was created to help fill these teacher choice and VR designer guideline voids. This chapter presented the two important affordances for VR and a new, applied rubric called QUIVRR, which has been made available to all stakeholders.

Appendix

Instructions: whole integers. Users can add 0.50 if they choose. Do not overthink precision though. This is modeled on a short and easy twenty-item rubric for “Cognitive Thinking Skills in Videogames” published by Rice (2007).

Double-barreled responses. The primary user for this rubric is a teacher trying to decide between, or to justify to others, the choice of an educational module. Teachers are busy. While it is cleaner to avoid queries with more than one construct in a single item response, that would result in more than thirty items, making this rubric more burdensome. Thus, users are sometimes asked to make judgments about *both* quantity and the quality with a single score. (Survey design hawks just need to take a deep breath.)

QUIVRR: Quality of Immersive VR in Education Rubric

Module Title: ____________________ Hardware ____________

(Author: M. C. Johnson-Glenberg)

Potential anchors: 0 = not present; 1 = low; 2 = some; 3 = moderate; 4 = high; 5 = very high.

A: Pedagogy/Content	Notes	Score (0–5)
1. Clear *learning goals* stated. Does module align well with learning objectives and critical thinking standards?		
2. *Suited to immersive VR.* Is content enhanced by 3D and/or enhanced by the presence afforded by VR?		
3. Does module support higher level *transformative learning?* See notes on the SAMR model and using technology optimally.		
4. Is *scaffolding* present? Does the module build up in complexity?		
5. *Active learning: quality only.* Could include user-driven choices and body movements; agency is included, and learners can kinesthetically practice learning goals.		
6. *Actions congruent to or reinforcing of the content?* Is there an authentic match between actions and agency and learning?		
7. *Guided exploration.* Is there some guidance or a beginning tutorial? Education modules should not be totally free exploration.		
8. Prompts for *metacognition.* Think about thinking: are there chances for reflection built in? (This could also include aspects such as outside of HMD prompts or working with a partner.)		
9. *Corrective feedback.* Feedback is given appropriately during activity.		
10. *Assessment.* Either in headset or afterward—more sophisticated than simple true/false.		
B: Mechanics		
11. *Designed for comfort.* Amount of text and eye strain. Example: Reverse coding: 0 = too much text/small objects to track, 3 = moderate amount of text, efforts made to keep comfortable, 5 = very minimal amount of text.		

12. Induction of *cybersickness.* Example: Reverse coding 0 = highly *likely* to lead to nausea and disorientation (e.g., roller-coaster); 5 = highly *unlikely.*		
13. Content is *interactive and manipulable: quantity.* This is about frequency and type of manipulation (relates to item 5).		
14. *Avatar creation.* Has multiple aspects under user design.		
15. *Avatar in play.* Movement matches to users' gestures, control, and ease over gestures. Example: 2 = module is all third-person point of view, but hand controls are well-mapped.		
16. *Overall interface* and ease of use. Interface intuitive and easy to navigate.		
17. *Sound* and its quality. Such as ambisonic, not distracting.		
18. *Haptics/other modalities.* Beyond visual and auditory stimuli (e.g., vibrotactics well integrated).		
19. *Engagement.* Holds attention, not repetitive.		
20. *Overall module quality/other.* What do you care about that is not listed above? Perhaps it could be key design aspects, treatment of gender and/or racial biases, creative use of low poly, empathy induction, or something else. Write in notes.		
Subtotal	**Subtotal**	
C: Bonuses *(Optional—these may be the norm soon)*		
21. *Adaptive.* Scales or adjusts in difficulty with learner's performance to stay in ZPD (zone of proximal development).		
22. *Collaborative.* Multiple users in same synchronous space.		
Final Score	**TOTAL**	

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Notes

1. For an example, see *Titans of Space-Mobile* version in the Go headset, version 2.5.5. http://www.drashvr.com/titansofspace.html. It is further described in the embodiment in education section.

2. The case could be made that empathy induction should be a separate profound affordance, but because the domain under study here is STEM education, empathy is not a focus. Empathy is subsumed under presence for our purposes, but we concede that those who design in the arts and humanities may hold different views.

3. The *Mimic* Go version will soon be deprecated. The Rift version can be found in the Oculus store for free at https://www.oculus.com/experiences/rift/2656510471032810. A new WebXR version can be found at www.embodied-games.com and https://xr.asu.edu/mimic.

4. There is also a *Titans of Space* version in the Oculus Rift which is more interactive and allows the user to leave the spacecraft and grasp and turn the bodies around. A study researching the novelty effect of VR and how embodiment in both versions of the *Titan* game affected learning in VR can be seen at Huang et al. (2021).

5. For examples of SMALLab Learning, see https://www.smallablearning.com/videos. For an original article on SAMR, see http://www.hippasus.com/rrpweblog/archives/2014/06/29/LearningTechnologySAMRModel.pdf.

6. This rubric pulls eyestrain out from the SSQ and treats it as an individual line item because so much text is often included in educational modules. We leave headache in the definition of cybersickness; eyestrain is only one pathway to a headache.

7. The *Catch a Mimic* game provides an interesting example. There is no navigation via locomotion, and no forced change in point of view, but there is a large amount of actionable content on the screen during play. Although much of the content is actionable, the capturing action (swooping the virtual net) is highly repetitive, and I would not score it as a 5.

8. The *Catch a Mimic* game does not show the body beyond hands, yet it was an effective learning tool. We must await further VR avatar research; for now, points are awarded along a continuum of allowing users more freedom and creativity in avatar construction.

9. This rubric is a work in progress in a rapidly evolving field; users are invited to download a fillable version at https://www.embodied-games.com/blogtools. Try it on a game, and please give me feedback via mina.johnson@asu.edu.

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V

SOCIAL COGNITION, EMOTION, MINDFULNESS

16

Mirror Neurons and Social Implications for the Classroom

Christiana Butera and Lisa Aziz-Zadeh

Introduction

Nearly three decades ago in a neuroscience laboratory in Parma, Italy, a monkey, some peanuts, and a happy accident stunned the scientific community. During an experiment, every time a monkey grasped a peanut, as expected the cells in a brain region (F5) being monitored would fire. However, after the experiment was over, it came as quite a surprise to the researchers when the very same brain cells that fired when the monkey made an action also fired if the monkey watched someone else move peanuts toward their own mouth, even if the monkey had not moved at all (Blakeslee, 2006). These cells became known as mirror neurons (di Pellegrino et al., 1992).

Since the discovery of visuomotor mirror neurons, auditory mirror neurons have also been discovered, where the sounds of actions activate our own motor representations of those actions (Aziz-Zadeh et al., 2004; Kohler et al., 2002). Although mirror neurons were originally discovered in the macaque monkey (di Pellegrino et al. 1992), a large body of evidence has accumulated in support of their existence in humans (for a review, see Fogassi & Rizzolatti, 2013), although there is some controversy around their role (for a review, see Hickok, 2009). The putative human mirror neuron system (MNS) is thought to consist of a frontal portion, primarily in the ventral premotor cortex (PMv) and the pars opercularis of the inferior frontal gyrus (IFGop), and a parietal portion, primarily in the inferior parietal lobule (IPL) (see figure 16.1). The MNS brain regions are activated both when performing actions and when observing or listening to others performing similar actions (Rizzolatti & Craighero, 2004). In other words, this system uses one's own neural motor representations to process and help understand sensory representations related to other people's actions. Through simulation, the MNS provides a "mirror" between others' actions and self-actions, enabling individuals to experience them firsthand. If you have ever had the experience of unknowingly crossing your legs when

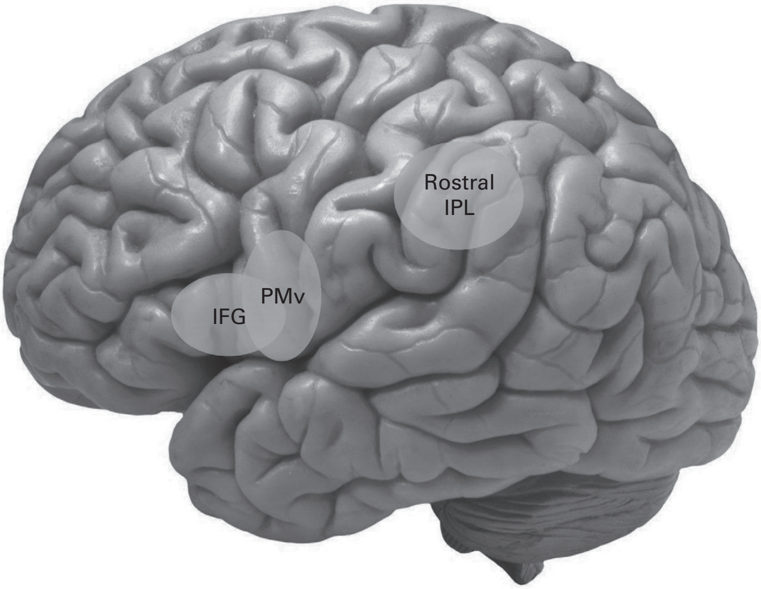

Figure 16.1
Areas of the human mirror neuron system. Lateral view of brain with frontal (PMv and IFG) and parietal (rostral IPL) mirror neuron regions. IFG, inferior frontal gyrus; IPL, inferior parietal lobule; PMv, ventral premotor cortex.

sitting across from someone else crossing their legs, then you have experienced your MNS at work!

The discovery of mirror neurons has captivated scientists and educators alike. The existence of mirror neurons revived a long-standing debate in psychology and neuroscience about how we process the actions and intentions of others. To some, mirror neurons provide a neurological support for the theory of embodied cognition (Rizzolatti et al., 1996).

Embodied cognition is a theory that posits that higher cognitive processing such as intention understanding, language, and cognition, may rely, in part, on fundamental brain regions involved in action production and sensory processing. This view is the opposite of cognitive or symbolic theories, and suggests that semantic knowledge, and much of cognition, is carried by sensorimotor representations (for review Caramazza et al., 2014). Understanding this system and how it interacts with other neural regions as well as the rest of the body and behavior may be one informative tool for devising better ways to improve learning and classroom environments. This chapter will explore how MNS regions, in collaboration with other neural networks, may contribute to larger motor and social-emotional learning processes. The mechanisms and functions of the MNS provide insight for the classroom setting in the context of (1) imitation learning, (2) empathy, (3) neurobiological evidence that learning is inherently embodied, and (4) evidence that learning requires involvement of emotional and social neural networks.

Imitation Learning: The Fallacy of "Do as I Say Not as I Do"

Imitation is critical for developing motor, communication, and social skills (Pfeifer et al., 2008). There are two main forms of imitative behaviors: imitative learning and social mirroring (or "chameleon effect"; Iacoboni, 2005). Early findings in newborns suggest that imitation is an innate ability (Meltzoff & Moore, 1977), and more recent work suggests that the strength of imitation ability is heavily influenced by early sensorimotor learning that occurs in an infant's cultural and social environment (for review, see Ray & Heyes, 2011). The range in type and number of imitated behaviors, as well as their accuracy, increases with greater exposure to those behaviors (e.g., Jones, 2007). Therefore, in development children can learn and practice how certain actions are executed by imitating them (e.g., Brass & Heyes, 2005).

Imitation is both a motor and a social behavior; in fact, it is important for numerous aspects of social development including pretend play (Nadel, 2002), reading facial and body gestures (Hurley & Chater, 2005), theory of mind (Goldman, 2005; Meltzoff, 2007), moral development (Forman et al., 2004), mirror self-recognition (Nielsen & Dissanayake, 2004), and joint attention (Rogers et al., 2003). Further evidence of this association can be seen in autism spectrum disorder, where imitation deficits occur in relationship with general social cognition deficits (Iacoboni & Dapretto, 2006). Imitation also influences interpersonal relationships in adulthood; individuals frequently unconsciously imitate the gestures and facial expressions of others (Chartrand & van Baaren, 2009), especially to adapt to demands of a social situation (e.g., Iacoboni, 2009). This social mirroring creates rapport and a shared experience between social partners (Chartrand & van Baaren, 2009).

As previously reviewed, the MNS may be involved in understanding other people's actions and intentions through embodied simulation (e.g., Fabbri-Destro & Rizzolatti, 2008). This system is involved in two necessary parts of imitation: action observation and action execution. Lesions in the IPL (an MNS region) can result in a deficit in imitation (Wheaton & Hallett, 2007), and lesions to the left IFG have resulted in impaired imitation of finger movements (Goldenberg & Karnath, 2006).

Another way of studying the neural correlates involved in imitation is through neuroimaging paradigms. An imitative music learning study of non-musicians showed that the MNS, along with motor preparation areas and the dorsolateral prefrontal cortex, is active when learning to play guitar chords through action observation (Buccino et al., 2004). In a large meta-analysis of functional magnetic resonance imaging imitation paradigms (Caspers et al., 2010), imitation tasks were consistently related to neural activation in a network of the IFGop, premotor, inferior parietal, intraparietal, primary somatosensory, and temporo-occipital areas. This network was active consistently regardless of what type of effector (hand, face, fingers, etc.) was being imitated, suggesting a general action imitation network.

These findings highlight two key points: (1) areas of the MNS (IFGop, PMv, IPL) are consistently active across imitation tasks, and (2) additional areas outside the MNS are involved in imitation and have simulation or mirrorlike properties, including the dorsal premotor cortex, supplementary motor area, posterior medial temporal gyrus, and middle temporal visual area (Caspers et al., 2010). Others have also shown support for a system that includes and extends the areas of the classic MNS in observation and imitation of actions (Iacoboni, 2009).

Children tend to imitate the goal of an action earlier in development rather than imitate the exact motoric and kinematic aspects of an action (Bekkering et al., 2000). Imitation may involve two processes: emulation and mimicry. An individual who emulates an action needs an understanding of the end goal or meaning of an action, whereas mimicry describes reproduction of low-level kinematic features and motoric aspects of any action, even if it is meaningless and does not have a goal (Hamilton, 2008). Emulation is carried out by coding goals of actions (in the IFGop), whereas mimicry is carried out by copying and coding of higher-order visual descriptions of actions (in the IPL and superior temporal sulcus) (Iacoboni, 2005).

Empathy

Empathy is a multifaceted construct defined by the ability to understand and experience the feelings of others (Dvash & Shamay-Tsoory, 2014). This capacity serves the evolutionary purposes of responding to social signals for reproduction, survival, parental care, and group cooperation (Preston & de Waal, 2002). Empathy is also a vital piece of human social interaction, necessary for formation and maintenance of interpersonal relationships, prediction of social expectations, and flexible responses to complex social scenarios (Thompson et al., 2016). Experiencing empathy can result in responses of sympathy, compassion, and prosocial action (Singer & Klimecki, 2014). Empathy allows us to understand others' experiences on an affective, cognitive, and sensory level.

Empathy as a construct can be delineated into dissociable dimensions of cognitive and emotional (sometimes called affective) components. Cognitive empathy refers to the ability to imagine and understand another person's thoughts, intentions, and feelings through an automatic (Frith & Frith, 2006) or intentional (Hein & Singer, 2008) process. Emotional empathy refers to the capacity for matching and sharing emotional responses to another individuals' emotional experiences (Davis, 1994). Although the mechanisms and functions of these dimensions do not completely overlap, they do interact in dynamic ways in social and emotional experiences (Zaki & Ochsner, 2012). Dysfunction of empathy and the MNS have been associated with various mental and developmental illnesses such as autism spectrum disorder, alexithymia, schizophrenia, and psychopathy (for review, see Jeon & Lee, 2018).

The MNS is likely to be only one of many neural systems involved in processing empathy, but it seems to play an important role in the processes. It would be a mistake to characterize the role of the MNS as solely for processing motor actions in a concrete and mechanical sense. Although this system does activate for observed, executed, and imitated actions, there is a complex integration between this system and other areas involved in perspective taking in order to viscerally feel empathy. One way of empathizing is through simulating the facial and bodily expressions of other people; in fact, those who spontaneously imitate others also tend to be more empathic (Chartrand & Bargh, 1999).

Indeed, the MNS has been implicated in both cognitive (for a review, see Kilroy et al., 2017) and emotional (for a review, see Dvash & Shamay-Tsoory, 2014) empathy models in collaboration with areas of the limbic system (i.e., the insula and amygdala). The MNS plays a role in processing the *intentions* of others' motor actions (Avenanti et al., 2013), particularly in social contexts (Gallese et al. 2004), and in emotional contagion—the phenomenon of having another person's emotions trigger similar emotions in the observer (Keysers & Gazzola, 2006). Several studies show that increased IFGop activity is associated with increased cognitive empathy ability (Kaplan & Iacoboni, 2006; Gazzola et al., 2006; Jackson et al., 2005). Numerous studies have also reported that the MNS is engaged in simulation of basic and complex emotions (Blakemore et al., 2005; Ebisch et al., 2008; Jabbi et al., 2007; Singer, 2006; Wicker et al., 2003).

A common self-report tool for empathy is the Interpersonal Reactivity Index (IRI; Davis, 1980), which has been used in many research studies in connection with MNS activation. During an observation task of disgusted facial expressions, activation of the IFG and the insula (a primary area for integration of visceral bodily state information and felt emotion) were correlated with higher empathy scores on the IRI (Jabbi et al., 2007). They found that empathy skills associated with both the ability to imaginatively transpose the self into feelings of fictional characters as well as in higher personal distress experienced in response to others' negative emotions were correlated with the strongest activation of the IFG and insula. Empathic concern measured by the IRI has been correlated with IFG activity in observation of painful facial expression (Saarela et al., 2007).

Interestingly, meta-analysis has indicated that the degree of activation of neural responses depends on the participant's real-time empathy during a task, further supporting simulation of felt emotion in MNS regions (Lamm et al., 2011). These responses are not limited to action observation and can be seen in response to other modalities that require imagery and prior knowledge such as auditory stimuli (Van Overwalle & Baetens, 2009). It is important to point out that in some cases MNS involvement in empathic processes has not been demonstrated (Fan et al., 2010).

Although the exact role and function in empathy needs further research, the sizable evidence cited here indicates an association between the MNS and empathic processing, though context and meaning may be important factors to consider (Aziz-Zadeh et al., 2018). Outside of mirror neurons in particular, the larger simulation or action-perception model of empathy offers a few key advantages other models. Simulation automatically, and therefore efficiently, uses internal motor knowledge to identify others' behaviors, it can explain imitation of motor to social information integration, and it can be used at an early stage of development, facilitating learning of several social and behavioral processes (Ferrari & Coudé, 2018).

Learning Is Embodied

How does the MNS relate to learning? Observational learning is one of the most basic mechanisms by which humans learn (Browder et al., 1986). Cognitive load theory proposes that human cognition is predisposed to learning by observing and imitating others; therefore, these strategies are optimal tools to use for acquiring and communicating knowledge (Sweller, 2010). Due to the fact that the MNS also responds robustly to observation and imitation of face and hand actions (Caspers et al., 2010), watching a teacher or another student demonstrate a skill and then imitating or executing it should allow for higher-quality understanding than, for example, only reading or hearing an explanation. Due to prior data indicating that the MNS is more active when observing videos of actions compared with still images of actions (Furl et al., 2015), this may imply greater effectiveness for use of dynamic rather than static visualizations. In fact, a meta-analysis found the use of dynamic visualizations to be more fruitful for learning outcomes, especially when animations were representational, realistic, and procedural-motor knowledge was involved (Höffler & Leutner, 2007).

Furthermore, the goal-directed nature of an action impacts the strength of activation of the MNS (Gazzola et al., 2007). In this way, it may be easier to understand educational concepts when goal-directed human movement is used to illustrate the concept. For example, a visual demonstration of subtraction might be best understood by a student if they watch a teacher or partner physically remove items from a group to represent subtracting a number of items, rather than seeing a picture of a group of items and then seeing a second picture of fewer items to imply subtraction. In that example, the goal-directed movement of a human action would more strongly activate the MNS. If the students were then to physically reenact these scenarios themselves, it would reactivate this system further, and strengthen the knowledge gained. Thus, observing others perform actions with the intent to imitate themselves, and then subsequent imitation or emulation, would strongly foster learning.

In addition, students need to understand the goals of both the teacher and the lesson in order for the MNS to be engaged effectively. This requires communication with students in order to have appropriate context for the information being covered, as well as an understanding of the intentions of the teacher (Immordino-Yang, 2009). Finally, the MNS is thought to be more active during contexts that are meaningful to the observer (Aziz-Zadeh et al., 2018), so integrating the lesson into a meaningful narrative for the student may also be beneficial.

Kontra and colleagues (2012) reveal how support for the embodied cognition model points to action experience as a powerful tool for learning. That is, if even abstract mental concepts can activate sensorimotor representations in the brain (Lakoff & Johnson, 1999)—and we know that imitation learning is a powerful form of learning—then lessons that engage the student at a sensorimotor level may prove to be more powerful forms of learning than traditional "behind-the-desk" methods (Kontra et al., 2012).

Keysers and colleagues (2018) address this topic in a review of neuromodulation and lesions studies, summarizing how the results of regions associated with the MNS contribute to the topic of embodied cognition. In their review, they reported large themes that are relevant for questions about how we learn and shape the meaning of social and motor actions. First, there is substantial evidence that undermining embodied representation by disrupting PM, SI, or

IPL impairs action prediction and the ability to coordinate action with others, a necessary skill for sensorimotor learning. Second, interrupting any of those areas (PM, SI, or IPL), or primary emotional processing areas like the insula or cingulate, decreases emotion recognition from facial and bodily expressions, which underlie the development of emotion understanding and social communication learning. Third, when *any* of the previously listed regions were disturbed (with a lesion or transcranial magnetic stimulation), it influenced the entire network of regions, lowering the activation of all other nodes in this network when one node was perturbed. The authors interpreted these findings to suggest that (1) embodied representations are inherently sensorimotor, (2) embodied representations are essential for processing and interacting with others, and (3) areas including putative MNS regions are working in a network to achieve motor and social understanding, and all regions are needed to achieve desired outcomes (Keysers et al., 2018).

Learning Is Emotion-Dependent

Just as the MNS uses embodied simulation to code and understand actions, other areas of the brain represent signals from the body to interpret feeling states and guide behavior. Social experiences create peripheral responses in the body, and these somatic representations facilitate feeling states, understanding, and prediction of actions of others (Damasio, 1996).

Immordino-Yang & Damasio (2007) review what patients with frontal lobe damage reveal about the interdependence of emotion and cognition. The evidence in these individuals demonstrates that learning, attention, memory, and decision making all rely on emotion processing. The authors go on to suggest that if emotion processing is a large component of learning, then asking students in school settings to focus on academic skills without attending to emotions is a near impossibility. Even more so, it does a disservice to students by emphasizing skills that will not transfer in a meaningful way to settings outside the classroom (Immordino-Yang & Damasio, 2007). The notion that learning requires personal emotional relevance has important implications for the classroom setting.

Indeed, the MNS may also have strong connections with reward circuits, which may be activated by positive emotions (Aziz-Zadeh et al., 2018). In general, when students perceive greater social emotional support from their teachers, they report greater enjoyment, hope, and pride (Titsworth et al., 2013) as well as better academic outcomes (Korpershoek et al., 2016). Creating an environment that feels emotionally supportive may be important, and perhaps may require an explicit focus on understanding emotions. Students are more likely to benefit from socioemotional learning interventions that are embedded in school culture across all staff and students, are consistently present in all environments including hallways and playgrounds, and have invited parental involvement (Farrington & Ttofi, 2009; Sugai & Horner, 2014; Wilson et al., 2008). Academic and socioemotional skills develop and perform together; therefore, lessons can be designed to promote both skills simultaneously. For example, programs can ground socioemotional lessons into course content through literature and social studies (e.g., Jones et al, 2014; Barr et al., 2015). Learning may be at its best when students can connect their academic skills to abstract, personal, and meaningful experiences (Immordino-Yang & Damasio, 2007) and educators are faced with the challenge of finding new ways to do so in each classroom.

Conclusion

In summary, the human MNS is thought to help process other people's actions and intentions, support motor and social imitation, and may contribute to our felt experience of the emotions of others through embodied simulation. This chapter reviewed how MNS regions, along with other neural networks, may contribute to better sensorimotor and socioemotional learning processes. It also supports classroom use of imitation learning, an emphasis on embodied learning strategies, and attention to social and emotional learning.

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17

Beyond the Social Domain: Autism Spectrum Traits and the Embodiment of Manipulable Object Concepts

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Introduction

Imagine teaching a child how to blow up a balloon. One strategy might be to teach the process step by step: grasp the thin neck gently, bring the hole to your mouth, and blow as hard as you can. Another strategy draws on the child's existing world knowledge: "pretend it's a whistle and you're blowing as *loud* as you can," you say. Which strategy is more effective? The answer likely depends on the child: there are considerable individual differences in how children (or adults, for that matter) rely on their experiences to build their understanding of the world (i.e., their *conceptual knowledge*). This implies that there will be individual differences in how children are best able to use conceptual knowledge to scaffold new experiences. In this chapter, we discuss how embodied theories of cognition (or, as we refer to them, *sensorimotor-based theories*) can inform educational practice by describing emerging research investigating how individual differences in autism spectrum characteristics affect the embodiment of conceptual knowledge.

The Role of Experience in Building Object-Concept Knowledge

Under sensorimotor-based (embodied) theories of cognition (e.g., Allport, 1985; Barsalou, 1999), conceptual knowledge is distributed across sensory, motor, and perceptual features—for example, a balloon is *squeaky, colorful, rubber, blows up, pops,* and so on. Understanding those features—and their conjunction: the balloon—relies upon the activity of the sensory, motor, and perceptual systems involved in real-world experiences with balloons. One way to evaluate this hypothesis about the representation of conceptual knowledge is by presenting people with words (or sentences) referring to concepts that are predominantly experienced in various sensory, motor, or perceptual modalities and examining the brain's response to those words. And indeed, studies using functional magnetic resonance imaging (fMRI) or other psychophysiological measures have demonstrated that concepts (presented as words) that are associated with a particular type of sensorimotor experience do elicit activity in parts of the brain actually involved in processing information or acting in that modality (e.g., action: Willems et al., 2010b; color: Simmons et al., 2007; sound: Kiefer et al., 2008; for review, see Meteyard et al., 2012; see also Davis & Yee, 2021).

There is strong evidence that this activation in sensorimotor areas during conceptual processing is attributable to these brain systems supporting conceptual knowledge. Some evidence comes from studies of disruptions to the brain systems underpinning action and manipulation. For instance, *apraxia* is a neurological condition that affects one's ability to perform motoric actions, and as predicted by sensorimotor-based models, people with apraxia show delayed access to the manipulation features of object concepts but not their visual features (Myung et al., 2010; see also Lee et al., 2014). Similarly, Parkinson's disease, a progressive neurological disorder, produces deficits (i.e., slowed processing) in understanding words and sentences referring to actions (e.g., "pinching cheeks," Fernandino et al., 2013a, 2013b; see also Buccino et al., 2018). Such deficits are not observed for abstract words and sentences (e.g., "saving cash").

Of course, acquired or progressive brain disorders might give rise to differences in object representation for reasons other than the motor impairment, so it is important to gather parallel evidence from healthy individuals. Our group (Yee et al., 2010) has probed how brain responses differ when a subject is presented with sequences of words that share certain characteristics in fMRI studies. We found that the activation of motor and action regions habituates (or *adapts*) when presented with consecutive words referring to objects that are manipulated similarly, suggesting that the same brain regions are involved in processing words related in manipulation similarity (Yee et al., 2010). Thus, there is converging evidence from studies of patients with neurological disorders and from neurologically healthy populations that the same brain systems underpinning action and manipulation also, to some extent, support our understanding of action- and manipulation-related concepts (for review, see Yee et al., 2013).

Another way to investigate the hypothesis that sensorimotor systems are implicated in conceptual processing is by scrutinizing conceptual *overlap* (i.e., by testing the factors that influence the degree to which any two concepts are represented similarly). Let us return to our example of using a whistle to teach a child how to blow up a balloon. According to sensorimotor-based theories, *balloon* and *whistle* share some conceptual overlap—both are held to the mouth with a pinching grip and have a designated end for blowing into. They share *manipulation* characteristics, despite differences in feel (soft versus hard), appearance (a colorful blob versus plastic or metal object shaped like a rounded letter *p*), and function (a decoration versus a noisemaker). Owing to this featural overlap, we would predict that, presented with a word like *balloon,* people would be faster to respond to a subsequent word when that word shares manipulation characteristics as in the case of *whistle,* but not when *whistle* is preceded by something unrelated such as *zipper.* This was exactly what was found in a study of healthy adults, which demonstrated that shared manipulability has a priming effect in language processing: in a lexical decision paradigm, healthy adults responded faster to words when the preceding word shared manipulation characteristics (Myung et al., 2006, experiment 1). Similarly, in an eye-tracking study using the visual world paradigm (e.g., Tanenhaus et al., 1995), Myung and colleagues (2006) presented adult participants with an array of four objects while tracking their eye movements. After hearing the name of one of the objects (e.g., *balloon*), participants fixated the manipulation-related object *whistle* more than unrelated objects like *zipper* and *plate* (Myung et al., 2006, experiment 2). Because of similarities in the way that we manipulate each object, our representations of *balloon* and *whistle* are partially overlapping; that is, our concepts for these objects share particular features.

We have established now that conceptual knowledge of object concepts is grounded in the sensory, motor, and perceptual systems actually engaged in experiencing those objects in the world. But at the outset we suggested that the optimal strategy for teaching a child how to blow up a balloon might depend on the individual characteristics of the child. Why? For sensorimotor-based theories, conceptual knowledge is *fluid* and *dynamic* (see Yee & Thompson-Schill, 2016)—that is, the way we understand the meaning of something depends on what we are doing at the moment (e.g., Davis et al., 2020b; Yee et al., 2013), what we have done recently (e.g., Yee et al., 2012), and critically for the present discussion, our *long-term experiences with the world* (e.g., Beilock et al., 2008; Chrysikou et al., 2017; Davis et al., 2020b; Hoenig et al., 2011; Kan et al., 2006; Willems et al., 2010a; Yee et al., 2013). In other words, results from our group and others suggest that an individual's experience over time shapes the way they understand the meaning of object concepts (for review, see "Individual Differences in Semantic Memory" in Yee et al., 2017).[1]

This is true in several ways. For instance, people tend to have more visual experience with *sunset* than with *breeze* or *galaxy,* and *sunset* is more reliant on the visual system for its understanding. This suggests that the degree to which a concept is experienced visually predicts the degree to which it is reliant on the visual system (Davis et al., 2020b). Analogous experience-dependent effects have been observed for other modalities (e.g., Yee et al., 2013). Further, people with expertise show different neural responses to expertise-relevant concepts. For example, expert hockey players, compared with novices, show greater neural responses to hockey-related language in areas of the brain related to action selection and implementation (Beilock et al., 2008), and similar effects have been observed in the auditory domain for musicians in response to language referring to music-related concepts (Hoenig et al., 2011).

Finally, gross differences in motor experience that emerge as a function of how individuals with different body capacities (e.g., handedness) experience the world affect how we represent conceptual knowledge. Right-handers and left-handers differ in the way they represent the meaning of manipulable object concepts: Right-handers show greater activation as compared to left-handers in the left (contralateral) premotor cortex for manipulable object concepts, but not non-manipulable ones (Kan et al., 2006; Willems et al., 2010a), and the effects of handedness on object-concept representations are sensitive to changes in experience, such as when a stroke patient loses the use of their right hand (Chrysikou et al., 2017).

Although it is becoming increasingly clear that gross differences in motor experience and ability affect the way we represent the meanings of object concepts, the role of more subtle differences is less clear. In the following, we propose that autism spectrum characteristics provide insight into more subtle differences in experience that nevertheless seem to affect the representation of conceptual knowledge.

The Role of Motor Function along the Autism Spectrum

Autism spectrum disorder (ASD) is a heterogeneous developmental disorder that presents with atypical social skills, including impairments in language and communication, and the presence of restrictive and repetitive behaviors and atypical sensory responses (American Psychiatric Association, 2013). Though not conceptualized as a core symptom of ASD, motor atypicalities have been reported since it was first diagnosed (Kanner, 1943), and they have recently been conceptualized as central to the diagnosis (e.g., Mostofsky & Ewen, 2011). Some of the motor atypicalities characteristic of ASD involve difficulties with movement coordination and reaching and grasping movements that are critical to how we interact with manipulable objects. People with ASD take more time to plan manual reaching motions and show more variability in their movement (Glazebrook et al., 2009), and it is thought that this reflects an issue with movement preparation as opposed to execution (i.e., a planning deficit; Rinehart et al., 2001). There are also some differences in gross motor domains.

For example, the gait differences between typically developing individuals and those with autism have been described as similar to the differences observed in people with Parkinson's disease (Vilensky et al., 1981), where those with autism show atypicalities in stride length, knee extension, and ankle flexion, among others. Motor difficulties in ASD individuals are coming to be recognized as a defining feature of the autism spectrum. What are the implications of this for how autistic people[2] develop, represent, and make use of conceptual knowledge?

Early motor experiences are a critical scaffold for higher-order cognition, a phenomenon recognized at least as early as Piaget (1950). For example, the development of neural perception-action circuits is critical to developing one's own capacity for skilled action as well as the ability to interpret that of others (for review, see Mostofsky & Ewen, 2011). The relationship between perceptual-motor integration and social-communicative skills in ASD was demonstrated by Linkenauger et al. (2012), who tested high-functioning adults and adolescents with ASD, as well as age- and IQ-matched typically developing participants. They found that impairments in affordance perception—where affordances are defined as an understanding of action possibilities in the environment (Gibson, 1979)—were characteristic of the ASD group. Specifically, the ASD group was more likely to make errors in recognizing whether an object can be reached from one's current position (i.e., reachability), whether one can grasp an object with a particular hand position (i.e., graspability), and whether one can fit one's hand through a hole of a given size (i.e., aperture perception). Furthermore, the error rate predicted social and communicative deficits in the ASD group only. These results support the idea that perceptual-motor integration is impaired along the autism spectrum and that such impairments are relevant for core symptoms of autism, namely, social-communicative deficits.

Beyond the social domain, these deficits in perceptuomotor function may have ramifications for how people on the autism spectrum understand conceptual knowledge (Eigsti, 2013; Moseley & Pulvermüller, 2018). As established in the previous section, sensorimotor experience is central to building conceptual knowledge, and this is true even in early word learning (Yu & Smith, 2012). A recent theory of embodiment in the ASD population (Eigsti, 2013) suggests that conceptual knowledge may be relatively more detached from the sensorimotor conditions involved in experiencing object concepts, which would then produce differences in embodiment of the motoric features of concepts.

Evidence in favor of this perspective comes from a study of adults with ASD who had age-appropriate cognitive abilities. Participants were asked to indicate whether they liked or disliked a set of Japanese kanji characters (e.g., 英) while positioned in either an approach (hands pushing up from under the table) or avoidance (hands pushing down from on top of the table) position. These postures have previously been found to modulate attitudes toward (formerly) neutral stimuli: approach postures facilitate more positive attributions and avoidance postures facilitate less positive ones (Cacioppo et al., 1993). The control participants were more likely to "like" kanji characters when observed in an approach position, but participants with ASD were not. Later, they were exposed to a new set of kanji characters, including the characters encoded previously in both approach and avoidance positions along with novel characters, and were asked to associate each character with either a positive or a neutral picture. In this phase, participants without ASD associated the kanji characters that were encountered while in an approach position with more positive potential meanings. This finding was not the case for participants with ASD.

These results suggest that the motor states associated with a stimulus are less relevant at encoding for people on the autism spectrum, and that those motor states do not carry forward when that stimulus is later reexperienced. If this is indeed the case, it implies that—unlike in a typically developing population—the sensorimotor stimuli involved in experiencing an object concept like *balloon* will not be reactivated when that concept is processed in the absence of the object itself, such as when hearing the word *balloon.*

Autism Spectrum Traits and Conceptual Embodiment

Only two studies to our knowledge have investigated how the neural representation of action verbs and object concepts might differ for persons on the autism spectrum. Speculating that the motor atypicalities observed in ASD might lead to reduced engagement of the brain's motor system when processing action verbs like *kick,* Moseley et al. (2013) found that compared with neurotypical controls the adults with ASD who had cognitive abilities in the typical range showed reduced primary motor cortex activity when passively reading both object- and action-related words. This difference was particularly pronounced for action words. Moreover, there was a negative correlation between autism spectrum characteristics and primary motor cortex activity in response to action words. It is likely that early emerging motor deficits lead to downstream consequences for semantic processing of action-related words (Moseley et al., 2013).

In a related study, de Vega et al. (2019) tested whether people high in autism characteristics[3] differed in an electrophysiological brain measure of motor processing called *mu suppression* when viewing videos of actions and pictures of manipulable and non-manipulable objects. Unlike the group low in autism characteristics, who showed normal mu suppression when viewing videos of actions and pictures of manipulable (but not non-manipulable) objects, those high on the autism spectrum showed no evidence of mu suppression. These results suggest atypical motor system activity. Moreover, there was a strong positive correlation between autism traits and the degree of mu suppression for action videos and manipulable objects, but not non-manipulable objects.

Collectively, these results suggest that individuals on the autism spectrum may have different perceptions of the motorically relevant features of objects and actions. Yet because the relevant studies to date have included a group with (likely) clinically significant autism traits, it is unclear whether differences in object-concept representations emerge across the subclinical autism spectrum. It also remains unclear whether the differences in neural activity that have been observed along the autism spectrum might produce differences in how the conceptual network is organized.

To address these issues, we recently investigated the degree to which individual differences in (subclinical) autism spectrum traits predicted the embodiment of manipulable object concepts (Davis et al., 2020a) using a visual world paradigm. Specifically, we asked whether there were differences along the autism spectrum in the degree to which any two concepts shared representational overlap as a function of similarities in manipulability. Typically, in the visual world paradigm participants view an array of objects on a screen, hear a "target" word referring to one of the objects, and then are asked to interact with (e.g., click on) the object to which the heard word refers. In our study, in the critical "manipulation-related" condition, participants heard a target word like "balloon," while they viewed an image of a *balloon,* an object related in manipulation characteristics, such as a *whistle,* and two unrelated objects like *plate* and *zipper* (figure 17.1a). In the control, "shape-related" condition, they heard a target word like *turtle,* while viewing an array that included an object similar in shape such as an *igloo* and two unrelated objects (figure 17.1b). The participants were instructed to click on the target object.

The most interesting results in this paradigm do not come from the eventual actions that are performed—virtually every participant clicks on the correct object on nearly every trial. Rather, the data of interest come from the patterns of eye movements that participants make while listening to the words and interacting with the screen. These patterns are taken to reflect the activation of the conceptual representations of the objects depicted on the screen as participants interpret what they are hearing. For instance, attention to the whistle when hearing the word "balloon" is taken to reflect partial activation of the concept *whistle.* In this experiment, we asked participants to complete the AQ (Baron-Cohen et al., 2001). We hypothesized that if autism spectrum characteristics predict the degree to which two objects sharing manipulation characteristics show conceptual overlap for a given individual, then individual differences in autism spectrum characteristics should predict the degree to which participants look to *whistle* upon hearing "balloon" (i.e., the *manipulation-relatedness effect,* as in Myung et al., 2006).

This was precisely what the data suggested. Upon hearing "balloon," looks to the whistle decreased as autism spectrum characteristics increased (figure 17.1c), but this was not the case for control trials in which the related object was similar in shape. Instead, in these control trials, looks to the shape-related object actually *increased* as AQ scores increased (figure 17.1d). These results showed that participants with higher autism traits were no less likely—and in fact, were somewhat *more* likely—to activate the concept *igloo* upon hearing the word *turtle.* On the other hand, *balloon* was less likely to activate the manually similar object concept *whistle* as autism spectrum characteristics increased. The motoric experiences typical of the autism spectrum seem to engender differences in the activation of conceptual knowledge.

What do the findings described in this section tell us about concept knowledge along the autism spectrum? In line with findings suggesting that the sensorimotor conditions when encoding a novel stimulus may not remain bound to that stimulus when it is later reencountered (Eigsti et al., 2015), work on how conceptual knowledge is represented as a function of autism characteristics suggests that motor and action systems are less (or atypically) involved when processing concepts typically experienced via motoric action. In the following section, we explore the implications of such findings for education.

Insights for Education across the Autism Spectrum

The implications of the present discussion are not restricted to students with an ASD diagnosis: the *broader autism phenotype* refers to typically developing individuals exhibiting subclinical autism traits (see Landry & Chouinard, 2016). Autism spectrum traits are observed at higher levels in family members of individuals with ASD (e.g., Landa et al., 1991). Such traits are also commonly

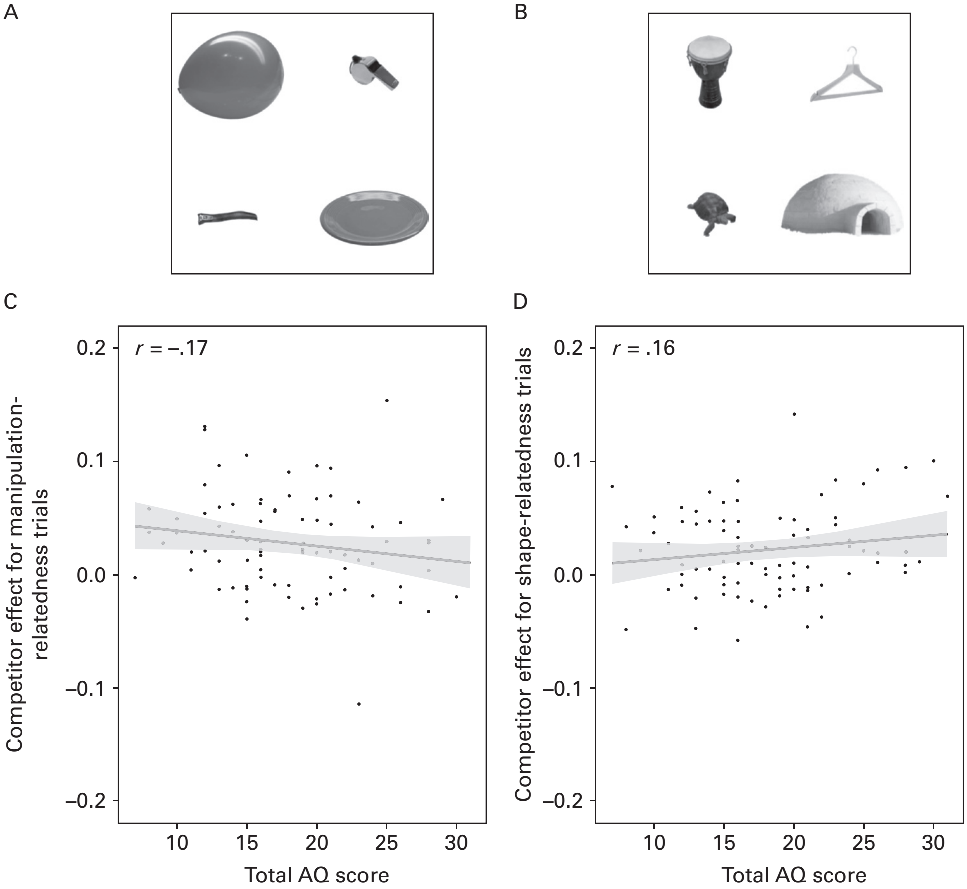

Figure 17.1
Top row: An example visual world paradigm trial for (A) the manipulation-relatedness condition, depicting (clockwise) a balloon, a whistle, a plate, and a zipper; and (B) the shape-relatedness condition, depicting (clockwise) a drum, a hanger, an igloo, and a turtle. (In the experiment, the displays were in color.) *Bottom row:* Correlation between total Autism-Spectrum Quotient (AQ) score and the relatedness effect (proportion of fixations to related item—proportion of fixations to average of two unrelated items) for (C) trials with a manipulation-related item (e.g., *balloon–whistle*) and (D) trials with a shape-related item (e.g., *turtle–igloo*). The relatedness effect is taken as the average of fixation proportions in the time window in which the relatedness effects emerged (600 to 1,100 milliseconds). Each dot (in each panel) represents one subject. Pearson's *r* correlations are superimposed on each panel.

observed in the general population. Because autism is such a heterogeneous condition, individuals with ASD vary greatly in their symptomatology; further, each of the symptoms characteristic of autism can range in severity from clinically significant on one end, to subclinical differences, to typical development on the other end (see Landry & Chouinard, 2016).

Because of this, we have consistently referred to autism spectrum "characteristics" or "traits" and have specifically noted studies testing for a correlation between these traits and some outcome, as opposed to only testing group differences. Thus, we take the findings described in this chapter to be reflective of the entire spectrum, not just those with a diagnosis. Our eye-tracking findings in particular (Davis et al., 2020a) demonstrate that discernable differences in conceptual knowledge emerge even without clinically significant autism spectrum traits.

Understanding the broader autism phenotype and how conceptual representations might vary across the autism spectrum will lend important insights into optimal learning strategies for this population. By asking a child to think of a whistle when blowing up a balloon, you are asking them to *simulate* their knowledge of a whistle and apply it to this novel situation. In sensorimotor-based theories, this simulation—that is, reenactment of the neural states involved in actually experiencing something—is a property of conceptual processing.

Thinking about a whistle leads to obligatory activation of the states involved in *experiencing* the whistle. But as we have seen in this chapter, the degree to which those experiential states are activated is subject to individual differences. In particular, an individual higher in autism spectrum characteristics may be less likely to activate the motor states involved in experiencing a whistle (and possibly more likely to activate visually relevant information, though our study was not designed to test this directly). For a child higher on the autism spectrum, thinking about a whistle to scaffold their learning of how to blow up a balloon may not be very helpful—the whistle may not obligatorily activate the sensorimotor states necessary to understand how to manipulate the balloon.

Now consider the alternative, more explicit strategy outlined at the beginning of this chapter for teaching a child to blow up a balloon. This strategy breaks the novel behavior into units of action: grasp the thin neck gently, bring the hole up to your mouth, and blow as hard as you can. From here, the connection to the whistle can be made clear: just as you would with a whistle, pretend you are making a loud noise and blow as hard as you can. In this way, we can effectively teach a novel behavior while still building feature-based connections between concepts (in this case, *balloon* and *whistle*) in the child's semantic network. Building these semantic connections via sensorimotor experience may be important not only for understanding balloons and whistles, but also for generalizing to novel categories (Vales et al., 2020).

The implications of these findings extend beyond practical “how-to” learning and into other important areas such as concept learning. For example, recent work has suggested that incorporating active body movement into learning physics concepts can be beneficial for learning (Johnson-Glenberg & Megowan-Romanowicz, 2017, this volume), and that the brain’s motor regions are a critical component of physics learning (Mason & Just, 2015). Given the atypical response of the motor system when individuals high in autism spectrum traits think about actions and manipulable objects (e.g., de Vega et al., 2019), the beneficial effect of embodied learning may require different paths for learners higher on the autism spectrum (see also Eigsti et al., 2015). An explicit learning strategy, in which the learning experience is broken into action units before building connections to existing embodied knowledge, may be a more effective path to embodied learning on the autism spectrum. Such an approach would maintain the benefits of experience-based learning in terms of building a densely interconnected semantic network, while being more suitable to individuals on the autism spectrum by incorporating an explicit learning strategy. These learning experiences might also benefit from emphasizing visual cues if these cues are more robustly available in ASD.

It is possible that differences in the degree to which motor experiences become integrated with other experience in ASD reflect a broader pattern involving a reduced connection between bodily sensations and social cues in ASD. Support for this comes from research on contagion effects: children with ASD do not exhibit contagious yawning in the typical developmental period (Helt et al., 2010). Moreover, although grasping actions in typically developing children are influenced by the presence of a distractor object that affects the reaching motion of another person, this is not the case for children with ASD. This suggests that while typically developing children form a joint representation of an object and an observer, children with ASD may be “immune” to the influence of an observer’s gaze (Becchio et al., 2007). What might be implicit and obvious to a typically developing learner may require explicit training for learners on the autism spectrum.

These results may also help us to understand the difficulties with socioemotional cues displayed in the ASD population. For many people, the physical cues associated with a particular state (i.e., the particular muscle tension associated with smiling) come to evoke those states, such that the physical act of smiling can actually elicit happy feelings (for review, see Laird & Lacasse, 2014). Although there is relatively limited evidence of this (e.g., Doody &

Bull, 2011), it is possible that people with autism struggle to link physical postures to the emotions that they convey (e.g., boredom, irritation, impatience). When most people see someone display a particular facial expression or posture, they gain implicit cues about that person's emotional state. By contrast, people with ASD may require explicit training and feedback in order to understand and remember the links between physical bodily states and emotions. Certainly, many therapy programs incorporate direct instruction on facial expressions of emotion, but we might consider expanding beyond the face and thinking about how to interpret postures.

A second (highly speculative) implication is that individuals on the spectrum may benefit from physical training and building their dexterity and motor skills. Of course, being physically active brings multiple benefits, including to general physical health, but perhaps it could also help strengthen connections between motor domains and other forms of sensory and cognitive experience (e.g., Gerson et al., 2015). By analogy, musicians appear to develop musical skills in part because of their learned associations of visual patterns (such as musical notation), auditory signals (notes played), and specific motor actions (the physical act of playing the instrument; Wan & Schlaug, 2010). This training appears to activate multimodal integration regions such as the intraparietal sulcus in a manner that may translate to other (non-musical) cognitive activities. Although the evidence for this is highly limited, there are many other health and social advantages to promoting physical activity.

Concluding Remarks

Sensorimotor experiences shape the structure of conceptual knowledge. Because experience plays such a vital role in developing concept representations, understanding how individual differences in sensorimotor experience contribute to differences in the structure of conceptual knowledge is critical.

Autism spectrum disorder is associated with significant differences in sensorimotor experience during development, and in this chapter we have described recent research showing that those differences manifest in differences in how conceptual knowledge is organized. We have also speculated on some approaches to embodied learning that emerge from these recent findings, though a better understanding of the nature of conceptual knowledge differences along the autism spectrum (including how conceptual knowledge is organized) will be critical to tailoring educational interventions for individuals on the autism spectrum.

Embodied learning may not be immediately intuitive to individuals on the autism spectrum, but combined with explicit connections to social cues and enriched physical education, children on the autism spectrum may benefit from embodied approaches to learning.

Notes

1. This is not to suggest that concept representations are entirely idiosyncratic. We also *share* many experiences, including a common language to refer to concepts, and it is likely because of this overlap in experience—both sensorimotor and linguistic—that we are able to communicate about the same things and generally understand each other (for discussion, see Davis & Yee, 2021).

2. To respect the varying preferences of those who use "person-first" language (e.g., "adult with ASD") and those who highlight the centrality of ASD to their identity and thus utilize phrasing such as "autistics" or "autistic adults" (Gernsbacher, 2017), the current paper uses both phrases.

3. The group high in autism characteristics scored at or above the cutoff of 32 on the Autism-Spectrum Quotient (AQ), which is a commonly used measure of autism traits where the total score reflects a continuous metric of autism spectrum characteristics (Baron-Cohen et al., 2001).

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18

Embodied Emotion, Emotional Granularity, and Mindfulness: Improved Learning in the Classroom

Jennifer M. B. Fugate and Christine D. Wilson-Mendenhall

Traditional Views of Embodied Emotion: Emphasis Solely on the Body

There is a rich theoretical history of how emotions engage the body, dating back to William James, who profoundly defined emotion by its experience (1884/1984). That is, an emotion occurs when a person senses the changes within the body (see W. James, 1884; Lange & James, 1922; for a critique of the James-Lange theory of emotion, see Cannon, 1927).[1] Most modern views of emotion emphasize the importance of feeling as a central aspect to emotion experience (for a detailed history of emotion theory, see Gendron & Barrett, 2009). Niedenthal proposed a theory of "embodied emotion" in which the experience, understanding, and perception of an emotion are similar (2007, 2008; Niedenthal et al., 2005). According to this view, understanding the concept of "anger" involves the activation of facial muscles associated with scowling as well as changes in the body's physiology (e.g., increasing heart rate, blood pressure, and skin conductance) and behavior (e.g., activating muscular tension).

Several studies' findings have supported bodily contributions in emotion, including facial feedback (Niedenthal, 2007; Tomkins, 1962, 1963). The facial feedback hypothesis (Buck, 1980; Tomkins, 1962, 1963) states that it is possible to experience the feeling of an emotion by moving the face in a prescribed way that is thought to be associated with a particular emotion. For example, participants who had Botox injections to the muscles associated with scowling were selectively impaired in reading sentences containing negative words and describing negative events (Havas et al., 2010). In another study, when participants were told to not move their faces, they reported a weaker emotional experience (Davis et al., 2009).

In some cases, it is even assumed that facial feedback can generate a specific emotional experience (Dimberg & Söderkvist, 2011). In one such study (Flack, 2006), participants who produced facial expressions (or bodily postures) that corresponded with specific emotions (i.e., anger, sadness, fear, and happiness) reported having higher emotional feelings for the specific emotion compared with other emotions.[2] In another study, participants who had their cheeks lifted, rated themselves as feeling happier, whereas when participants had their cheeks lowered, they rated themselves as feeling sadder (Mori & Mori, 2009). Similarly, voluntary production of facial movements associated with an emotion can produce changes in physiological parameters such as heart rate, skin conductance, finger temperature, and muscle tension associated with that emotion (Levenson et al., 1990).

Body posture is also thought to cause an embodied experience. In one study, participants who received positive feedback on a test reported feeling less proud of their accomplishments if they had been assigned to adopt a slumped-over posture (versus erect posture) (Stepper & Strack, 1993; see also Valiente et al., 2012). Finally, in an additional study that tested the congruency between valence of a stimulus and the affordances of the body, participants were slower to push a lever away from them to indicate a stimulus change that was positive compared with when it was negative (Duckworth et al., 2002). The reverse was true for participants who pulled a lever toward them. Therefore, matching the emotional reaction (e.g., *positive* and pulling toward, or *negative* and pushing away) facilitated emotional responding.[3]

Embodied Emotion from Psychological Constructionism: Emphasis on Language

Consistent with some of the most recent and influential theories of embodied or "grounded" cognition (see Macrine & Fugate, chapter 1 in this volume), constructionist perspectives of emotion suggest that emotion categories are represented as probabilistic patterns that develop from prior experience, including coordinated bodily (interoceptive and visceromotor), sensory (e.g., visual, auditory, etc.), and motor information (Barrett, 2017; Wilson-Mendenhall, 2017; Wilson-Mendenhall et al., 2011). Because emotion categories are grounded in sensorimotor experiences, they are specific to an individual; therefore, there is no clear "prototype" across individuals (Wilson-Mendenhall & Barsalou, 2016). According to these views, emotion categories (e.g., anger, fear, happiness) are better thought of as "populations" of situated, experiential patterns rather than a single prototype (Barrett, 2014). Because the situational patterns that develop for a given emotion category (e.g., anger, fear, happiness) are varied, it is often the consistent phonological form of an emotion word that anchors these patterns to a given emotion category (see Barrett, 2006a, 2014; Betz et al., 2019; Hoemann et al., 2020; Lindquist, 2017; Lindquist et al., 2016).

In one such perspective (Barrett, 2006a, 2006b, 2014, 2017), an emotion category becomes increasingly complex as different situational instances are labeled with an emotion word. Because over time words become linked to sensorimotor patterns, an emotion word like "anger" can result in the brain simulating these experiences to determine whether oneself or someone else is "angry." Therefore, after a word is consistently yoked to a sensorimotor pattern, it serves as an anchor for simulating those patterns. As such, it "activates" embodied knowledge. Because emotion words help to activate sensorimotor patterns, they can facilitate the processing of sensory information that is consistent with the particular emotion category (Barrett, 2006b, Wilson-Mendenhall et al., 2011; see reviews by Fugate & Barrett, 2014; Lupyan & Ward, 2013).

This view is similar to Borghi's idea of "words as social tools." As one of the basic premises of her theory, Borghi states that "linguistic mediation is more crucial for abstract concepts than for the representation of concrete ones, given that the scaffolding function of the physical environment is less powerful" and that "abstract concepts (*including emotions*) and words are more affected by differences between languages than concrete ones; that is, their meaning changes more depending on the cultural and linguistic milieu in which they are learned" (Borghi & Binkofski, 2014, emphasis added).

Both these ideas bear resemblance to the idea that abstract representations are created from concrete representations by way of metaphorical extension (Gallese & Lakoff, 2005; Lakoff, 1987, 2012; Lakoff & Johnson, 1980). Lakoff extensively documented the use of metaphoric language to ground spatial, body-centric, and even emotional metaphors in concrete representations (e.g., in English, *love* is often conceptualized as a journey, a game, or a flower) (Lakoff & Johnson, 1980). Therefore, the function for such extensive use of metaphors in English as well as other languages might be to provide a tangible "grounding" to the body and to the physical world.[4]

The Development of Embodied Emotion Categories through Language

In most constructionist theories of emotion, language plays a critical role in the development of adaptive emotion categories (Barrett, 2006a, 2009, 2014; Russell & Widen, 2002; Widen, 2013; Widen & Russell, 2008; for reviews, see Hoemann et al., 2020; Shablack & Lindquist, 2019). Many developmental studies show that language (e.g., words) can serve as the *essence* that links members of one category with others in the category (Xu et al., 2005), and that words facilitate learning new categories (Lupyan et al., 2007). Words bind together situated instances into a meaningful category representation. The result is that individual tokens are thereby linked into cohesive types (concepts) through words. In fact, infants routinely use the phonological form of words to make conceptual inferences about novel objects that share little perceptual similarity (e.g., Dewar & Xu, 2009; Xu, 2002). In one example, a shared linguistic label (even a made-up one) directed infants to group together objects that otherwise did not share strong perceptual similarities (Plunkett et al., 2008).

One way in which this might be done during development is through a child's early interaction with his/her caregivers within the context of their culture (e.g., Denham et al., 1994; Halberstadt & Lozada, 2011). Children's emotional utterances at two-to-four years old correlate with their mother's emotional word knowledge and use (Cervantes & Callanan, 1998), and children whose parents discuss emotions with them at an early age (thirty-six months) have better emotion understanding at six years (Dunn et al., 1991). Specifically, parents' explanations of internal feelings are thought to scaffold a child's own ability to identify and describe the experiences within themselves and in others (Saarni, 1999; Yehuda, 2005). Children who are more apt at recognizing and expressing their emotions worry less and show fewer signs of depression than children who struggle to convey their emotions (Rieffe et al., 2007). Similarly, children's emotional understanding is predictive of their social and emotional regulation skills and even their academic performance (Halberstadt et al., 2001, 2013).

The development of emotion categories follows a similar trajectory across cultures, with infants experiencing basic bodily sensations (e.g., negative and positive-valenced feelings) and then making more fine-grain distinctions among these more basic sensations (Hupka et al., 1999; Russell & Bullock, 1986; Shablack et al., 2019; Widen, 2013; Widen & Russell, 2008). For example, toddlers initially describe their own feelings and others' feelings with the words that reflect large differences in valence, such as *happy* versus *sad* or *mad.* By age five, however, they typically incorporate *afraid, disgust,* and *surprise* (Widen & Russell, 2003). Moreover, children by this age now recognize these emotions in others. That is, they are now able to sort *negative faces* into *angry* and *fearful* faces in perceptual sorting tasks (Widen & Russell, 2008). Emotion labels also better predict a child's ability to match emotional faces compared with different visual pictures of the same emotion (Russell & Widen, 2002), an effect known as "language superiority effect."

The Continued Importance of Language in Dissociating Embodied Concepts

Emotion words are not only important for children during development to learn emotion categories, but emotion words also continue to have an impact on the development and use of emotion categories during adolescence and across the life span. There are an increasing number of studies that show the importance of emotion words (and emotion language) and the effects that they have on embodiment (Niedenthal et al., 2009; Moseley et al., 2012). Niedenthal and colleagues (2009) used facial electromyography to measure participants' facial muscle reactions when viewing emotional (and nonemotional) words and either performing a nonembodied, perceptual task (e.g., identifying whether the word was capitalized) or an embodied task (e.g., evaluating the meaning of the word). The response of facial muscles was emotion-specific for the emotional words. In another study, Moseley et al. (2012) showed passively reading emotional words activated the parts of the brain related to processing face- and arm-related gestures associated with specific emotions. Moreover, the same areas of the brain specific to an emotion (e.g., anger) were also activated for more abstract (less embodied) emotion words, including "spite."

These findings are in line with another large body of literature that shows emotion words affect emotion perception at various levels of cognitive processing. In one study, the participants had a difficult time deciding whether two emotional faces matched when an emotion word was satiated (such that the word became meaningless) (Lindquist et al., 2006). Under similar conditions of semantic satiation, the participants also did not show repetition priming of emotional faces (Gendron et al., 2012), suggesting that the same exact face was not recognized by the visual system in the absence of emotion words.

In another study, participants were more likely to say that a distractor emotional face was a previously seen target face when primed with an emotion word (compared with when primed with a nonemotional control word) (Fugate et al., 2018, studies 1 and 2). Specifically, the participants had less sensitivity to detect differences between possible emotion category targets. This effect was later expanded upon in a study showing that emotion words both reduce *within-category* variability for emotional faces and maximize the difference *between* faces from different emotion categories (Fugate et al., 2020), which is consistent with categorical perception studies of emotion (e.g., Fugate et al., 2010; Fugate et al., 2021; Roberson & Davidoff, 2000). In these studies, the participants' abilities to detect differences between emotional faces from *different* emotion categories were enhanced when they had access to individual emotion words or labels (for a review, see Fugate, 2013). Although the latter studies do not explore embodiment per se, they do show that the emotion words are integral to the perception and experience of discrete emotions such that they help to "anchor" affective changes.

Emotional Granularity

Emotional granularity, also known as emotion differentiation, describes the ability to make fine-grained distinctions between similarly valenced affective feelings (Barrett, 1998; Tugade et al., 2004). People who are low in emotional granularity tend to differentiate emotions only on arousal or valence, whereas those high in granularity have more fine-grained categories of emotion (Barrett, et al., 2001) and are able to distinguish among similarly valenced emotions with ease.[5] Individuals with high granularity are able to distinguish feelings of irritation from impatience, agitation, excitement, and annoyance.

Individuals who use emotion words in a granular manner are less prone to maladaptive behaviors, such as binge eating (Dixon-Gordon et al., 2014), alcohol abuse (Kashdan et al., 2010), nonsuicidal self-injury (Zaki et al., 2013), and physical aggression (Pond et al., 2012). Emotional granularity is thought to be a transdiagnostic vulnerability across a range of mental health disorders (Kashdan et al., 2015).

Individuals higher in granularity also report more flexible emotional regulation abilities (Barrett et al., 2001; Boden & Berenbaum, 2012), have a less reactive coping style (Tugade et al., 2004), and are less biased by incidental emotions when making moral decisions (Cameron et al., 2013). Barrett and colleagues (2001) showed that greater emotional granularity leads to better emotional regulation and may serve as a protective factor against more destructive emotional regulation strategies. In one recent study, adolescents' positive and negative emotions were recorded with experience sampling over a two-week period. The ability to differentiate negative emotions was related to less negative intensity and propensity, as well as increases in believing that they could change the emotion (Lennarz et al., 2018).

Others have suggested that emotional differentiation can highlight the discreteness of a feeling, which may in turn make experiences easier to regulate (Lieberman et al., 2007; Kassam & Mendes, 2013). Other studies have found low granularity might cause ineffective use (but not necessarily ineffective selection of regulation strategies), which may hinder successful emotion regulation (Kalokerinos et al., 2019).

Knowing one's own feelings may also help with understanding others' feelings (Saarni, 1997). Kashdan and Farmer (2014) proposed a model in which individuals who experience their emotions as more granular will first use emotion words to differentiate what is felt in a given moment and then use these specific emotion words to regulate their emotions as well as to perceive emotions in other individuals.[6] Furthermore, emotional granularity is correlated with emotion perception performance (i.e., when participants are asked to judge the state of a target individual) (e.g., Israelashvili et al., 2019). This finding is suggestive that the training of emotion words in adults could improve emotion perception and sociocognitive capacities that are contingent on emotion perception.

In addition, emotion perception disorders, including autism spectrum disorders, are often mediated by language deficits, where successful intervention focuses on learning to label emotional stimuli (e.g., Baron-Cohen et al., 2009; Davis et al., chapter 17 in this volume). Indeed, emotion perception disorders for individuals on the autism spectrum are mediated by alexithymic traits (Cook et al., 2013). Alexithymia is a disorder defined by a difficulty to identify, understand, and express emotional information (Bagby et al., 1986). People with alexithymia either possess little knowledge about emotion concepts or have undifferentiated knowledge (i.e., less granularity) of emotion concepts.

Mindfulness and Emotional Granularity

The awareness practices that characterize mindfulness-based interventions are thought to improve emotion regulation by cultivating a more fine-grained awareness of what is occurring in one's mind (Hill & Updegraff, 2012; Roemer et al., 2015). Furthermore, the way in which internally oriented observation occurs in many mindfulness practices—with curiosity, openness, and a less reactive "decentered" stance—supports dismantling and defusing destructive emotions (Roemer et al., 2015).

One of the most widely used measures employed to assess trait-like individual differences in mindfulness, the Five Facet Mindfulness Questionnaire (FFMQ), includes a construct related to emotional granularity: *describing* (Baer et al., 2006). The describing facet extends beyond emotions to mental states more generally. Example items from the FFMQ describing subscale include "I'm good at finding words to describe my feelings," "I can easily put my beliefs, opinions, and expectations into words," and "It's hard for me to find the words to describe what I'm thinking" (reverse scored) (Baer et al., 2006). Higher scores on the describing facet are associated with greater self-reported attention to and clarity of emotional feelings, and fewer symptoms of alexithymia (Baer et al., 2006). The FFMQ describing facet is also associated with scenario-based measures of negative emotional granularity that draw on common life events (Boden et al., 2015) or personal experiences (Fogarty et al., 2015), providing evidence that the two constructs are related when emotional granularity is assessed with measurement techniques other than traditional self-report.

Meta-analyses of individual differences in mindfulness show a consistent, moderate relationship between the FFMQ describing facet and mental health symptoms, in which higher scores on the describing facet are associated with fewer symptoms of anxiety, depression, and related disorders (Carpenter et al., 2019; Mattes, 2019). Better quality of life is also consistently associated with higher self-reported describing ability (Boden et al., 2015; Mattes, 2019).

Describing is distinct from, but related to, other facets of mindfulness. For example, psychometric evaluation of the FFMQ demonstrated moderate correlations between describing and other facets of mindfulness, such as acting with awareness, nonreactivity, and nonjudgment (with each facet separating in factor analysis) (Baer et al., 2006). Relative to other mindfulness facets, describing showed the strongest cross-sectional relationship with social outcomes in a recent meta-analysis (Mattes, 2019), which may speak to the role granularity plays in perceiving and communicating with others.

Evidence from intervention studies suggests that mindfulness practices may increase granularity in adults. A recent meta-analysis indicated that self-reports of the describing facet increase with mindfulness training (Quaglia et al., 2016; but see Baer et al., 2019 for evidence that this effect is diminished when active control conditions that also likely train granularity are used). Moreover, pre-post increases in describing showed moderate magnitude associations with pre-post increases in mental health (e.g., fewer symptoms of anxiety and depression; better quality of life) (Quaglia et al., 2016). In line with this evidence, a meta-analysis of the relatively few studies that examined alexithymia as an outcome (four in total) indicated that after mindfulness training the participants were better able to attend to and describe internal emotional experiences (Norman et al., 2019).

The only intervention study to examine granularity using repeated, momentary experience sampling instead of traditional self-report found that increases in the granularity of negative emotions after mindfulness training were mediated by changes in acceptance and decentering (even when controlling for changes in negative affect) (Van der Gucht et al., 2019). This result suggests that learning to observe one's internal emotional experiences with a more nonjudgmental and distanced perspective may be central to cultivating emotional granularity in this context. While this mediation analysis is suggestive, this study design did not include a control group and thus was not a randomized controlled trial.

In summary, cross-sectional evidence suggests higher granularity of emotions and mental states are related to greater trait-like mindful qualities and to beneficial outcomes. The initial results from intervention studies further suggest that emotional granularity can improve with training, and that these changes may support better mental health.

Implications for Embodied Emotion in the Classroom

Classrooms and daycare centers should capitalize on teaching children to acquire emotion words and to improve their emotional granularity. Teaching children a variety of emotional vocabulary helps them label their own affective feelings, ultimately leading to increased emotional granularity, positive social outcomes, and school success (e.g., Hagelskamp et al., 2013). This can be done initially early in development with pairing basic emotion words with naturalistic pictures of people showing prototypic emotional "expressions" and labeling emotional behaviors when they are seen in the classroom. Situational information can later be added to help understand such "expressions" in context, and the use of situational language can then be incorporated into the category knowledge. Such activities are the basis for many emotional-intelligence packages that have been used in the classroom already.[7]

Building on evidence of the beneficial impact of mindfulness-based interventions in adults, an emerging research focus is to develop and study mindfulness-based interventions in schools. A recent meta-analysis showed consistent increases in mental health and well-being outcomes after mindfulness training in school settings, with the greatest benefit observed during late adolescence (ages fifteen to eighteen) (Carsley et al., 2018). In general, emotional granularity is lower during the adolescent period relative to childhood and young adulthood, which may indicate grappling with emotional experiences that are becoming more multifaceted (Nook et al., 2018). Because mindfulness-based programs involve observing and labeling one's internal experiences, training-related changes in emotional granularity may be one pathway to improving mental health during this time. This future research direction is consistent with recent recommendations to use more diverse outcome measurements and investigate the "active ingredients" of mindfulness-based interventions in schools (Felver et al., 2016).[8]

Beyond the classroom, many therapies focus on strategies such as cognitive restructuring to alter one's experience of emotional states. Not surprisingly, labeling is often a part of cognitive behavioral therapy to treat emotional disorders (Jamieson et al., 2012; Pennebaker & Beall, 1986). In one study, depressed individuals had less-differentiated negative emotion experiences compared with nondepressed individuals (Demiralp et al., 2012).

Mindfulness-based therapies are also used to treat emotional disturbances, stress, and anxiety (Goldberg et al., 2018). The results of a recent meta-analysis suggest that mindfulness interventions with youth may be particularly beneficial for clinical populations (Zoogman et al., 2015). Moreover, across a broad range of subsamples and outcomes, mindfulness most robustly addressed symptoms of psychopathology (relative to other outcomes that were measured such as attention, social skills, psychophysiological outcomes).

Therefore, treatments that focus on more adaptive forms of emotion processing, including differentiating broad emotional experiences, might serve as a protective factor against emotion dysregulation and mental illness. Specifically, teaching individuals emotion words and to examine their own emotional experiences is likely to facilitate more granular emotional knowledge and allow individuals experiencing emotional difficulties to reconceptualize generalized negative feelings, which makes these individuals more likely to engage in adaptive emotion processing within themselves and also be better at emotion perception of others.

Conclusion

In this chapter we have reviewed the evidence that individual categories of emotions (that are the basis for perceiving and experiencing discrete emotions) are learned when sensorimotor and bodily affective changes are learned within a situational context and become "linked together" by the application of emotion words. Improving a person's emotional vocabulary (to increase emotional granularity) is linked to improved emotion perception of others, and improved emotion regulation and increased mental health and well-being in the self. Finally, mindfulness improves these outcomes, most likely by increasing the ability to attend to and describe embodied affective changes (thereby increasing emotional granularity).

In fact, burgeoning research suggests that improving emotional granularity might help protect individuals from a wide array of mental health disorders, especially adolescents who are disproportionately affected by certain disorders (e.g., depression, anxiety, eating disorders). Moreover, adolescence is a time when individuals experience rapid growth in the prefrontal cortex and increases in the connections between it and the temporal lobe, which support language acquisition and cognitive representations. Therefore, adolescence might be the perfect time to improve emotional vocabulary to facilitate granularity and ultimately enrich the conceptual structure of emotion categories.

Classrooms and school settings should capitalize on teaching emotion vocabulary and mindfulness to individuals to not only improve emotional interactions and regulation but also to improve attention, focus, and cognitive awareness, which all facilitate academic performance.

Notes

1. Although some of these views place the experience of the emotion as central to the emotion, most more modern models actually suggest that the feeling (subjective experience) is the reaction—not the cause—of the emotion.

2. With some overlap between anger and disgust, and fear with surprise.

3. For more cognitively mediated explanations, see Cacioppo et al. (1993), Chen and Bargh (1999), and Förster and Strack (1998).

4. See Gómez and Glenberg (chapter 5) and Kaschack and McGrew (chapter 6) in this volume.

5. Some individuals seem to be more arousal focused and some more valenced centered when describing their emotions (Barrett, 1997).

6. For a review on how this idea is related to empathy and social connectedness, see Butera and Aziz-Zadeh (chapter 16) in this volume.

7. For one such successful example, see Brackett et al. (2012) for the RULER approach: recognize, understand, label, express, and regulate.

8. Recent reviews and meta-analyses also highlight the need for more randomized controlled studies (i.e., experimental designs), use of active control comparison conditions, analyses that account for students nested in classrooms and schools, and reporting full details of student characteristics (Felver et al., 2016).

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Conclusion

Sheila L. Macrine and Jennifer M. B. Fugate

This volume unpacks new views of knowledge acquisition and illuminates the latest empirical information on how embodied cognition can be applied across the content areas of reading and language, science, technology, engineering, and mathematics (STEM) education, learning differences, instructional technology, and social-emotional learning. As a result, the chapters contribute to the growing field of embodied cognition with implications for embodied learning in the classroom.

Some of the key themes that emerged, which provide room for future research on embodied cognition, include bodily-based engagement, metaphor-based interactions, gestures, mirror neurons, affordances, emotion language, embodied emotion, environmental design, physical versus digital writing, physical and virtual manipulatives, and the development of taxonomies and assessments. These evidence-based findings and applications allow educators to inform their own pedagogy for the classroom, in keeping with the current mandates of the Every Student Succeeds Act of 2015 (ESSA, 2015).

The volume opens by tracing the historical views on thinking and learning, including the philosophical and theoretical problems with Cartesian dualism. The rest of the sections include chapters that speak to different content areas and come together in support of sensorimotor and body-based learning.

Translational Learning Sciences Research

An emerging paradigm called translational science research, as endorsed by the National Center for Advancing Translational Sciences (NCATS) at the National Institutes of Health (NIH), supports, promotes, and disseminates research (typically biomedical) that builds on basic scientific findings to be translated into applications and treatments for public health (NCATS, 2018, 2019). Simply put, translational science research is the process of quickly turning findings from the laboratory, clinic, and community into interventions to improve the health of individuals and the public (NCATS, 2019).

Yet in terms of education few educators are privy to the research advances in the science of learning (Weinstein, et. al., 2018). Henry Roediger stated that "we cannot point to a well-developed translational educational science, in which research about learning and memory, thinking and reasoning, and related topics, is moved from the lab into controlled field trials (like clinical trials in medicine)" (2013, p. 1). He argued for the development of a translational educational science that could be applied to cognitive psychology as it is to medicine. In 2017, the James S. McDonnell Foundation (JSMF) launched a program supporting use-oriented research to expand our understanding of teachers as learners and as agents of change in education.[1] The resultant study panel reported that "systemic education reform efforts based on integrating *evidence-based practices* into classrooms will likely continue to encounter *limited success* unless such attempts [are] supported by a strong knowledge-base built on a scientific understanding of how teachers acquire and use new knowledge, new curricula, and new approaches in their professional practices and in the context in which they teach" (p. 1).

Collectively, the forward-thinking authors in our volume present examples of what we refer to as *Translational Learning Sciences Research* (Macrine & Fugate, 2021) in an effort to translate and bring the latest embodied neuroscience and cognitive science findings into the classroom to enhance educational practice. That said, our model informs embodied learning theory through seven goals: (1) making sense of and disseminating clinical and empirical research findings; (2) closing the gap between research and application; (3) combining cognitive psychology and pedagogy to share pertinent information; (4) improving teaching and learning through embodied applications; (5) confirming or debunking current trends; (6) elucidating conceptual frameworks for sensorimotor and body-based learning; and (7) recommending curriculum, designs, technology, and development to inform policy.

In response, our contributors have demonstrated *Translational Learning Sciences Research* (Macrine & Fugate, 2021) as they present their scientific findings, approaches, and principles of cognitive science and neuroscience, leading to the creation of evidenced-based, efficient, and effective embodied applications (Gilliland, 2019). That said, this volume highlights the pertinent and emerging research on how to integrate embodied cognition across content areas. It does this by presenting practical advice for future practitioners, cognitive scientists, educators, and educational psychologists to make relevant connections, adoptions, and meaningful associations with learning. This volume further emphasizes a need for appropriate professional development programs that foster the interdisciplinary understanding of embodied approaches across various disciplines (You, 2017). In other words, this is where science meets the real world of schooling. We propose four steps pertinent to *Translational Learning Sciences Research* (Macrine & Fugate, 2021) applied to embodied cognition, which we have adapted from our seven goals:

1. Promote the multidirectional and multidisciplinary integration of basic embodied research with the long-term aim of improving the teaching and learning.
2. Compile the embodied research to be analyzed, translated, and make connections to improve pedagogical approaches and to elucidate or to debunk current trends in teaching and learning.
3. Develop resources and tools to help individuals at all levels of expertise develop a better understanding of embodied learning.
4. Focus on the creation of appropriate embodied curriculum and the development of taxonomies to identify objectives and track outcomes that will assess whether program objectives and competency requirements are being met.[2]

We address step 1 by carefully curating contributions from leading experts in the field to argue that embodied cognition provides the scientific evidence to create pedagogically sound practices. Further, these contributors point to behavioral and neuroimaging procedures to show how observational and physical learning overlap to form the basis of embodied cognition (Cross et al., 2009, p. 315). For example, in parts II and III of this volume, we include some striking embodied approaches on how self-generated action affects cognitive development, including reading and mathematics skills. Using functional magnetic resonance imaging and other neuroimaging methods, James (chapter 4) illustrates that early handwriting practice leads to better letter recognition and literacy development. Gómez and Glenberg (chapter 5) show how vocabulary acquisition can be enhanced by shared communication, simulation, physical pantomime or gesture, and/or grounding of information to concrete objects (part II). Boaler (chapter 8) shows how finger perception predicts learning math all the way through college (part III).

To address step 2, we present table 19.1. In this table, we identify key findings from individual chapters, and translate them into direct action/advice for the classroom.

To address step 3, we provide a resources section as an appendix that lists all the physical and electronic activities, software applications, games, and devices described. This provides the reader with an easy go-to resource for finding the information to implement as they see fit.

Table 19.1
Key embodied learning research and applications for classroom teaching

Key findings	Actions/advice
• Hand-printing practice in preschool and even in the early elementary years is important for letter learning and early literacy.	• Children should practice self-generated handwriting and printing to improve letter knowledge as well as to improve subsequent literacy and symbolic understanding. • Children should practice the strokes involved in motor program for each letter (the direction, lines, and curves are not accidental). This is mainly lost on the keyboard.
• Vocabulary is acquired when the meaning of a word is embodied through simple bodily experiences. Embodiment-based interventions show promise for improving children's reading comprehension skills. Language comprehension relies on connecting linguistic elements (e.g., the words and phrases in the linguistic input) to sensorimotor representations (e.g., the perceptual or motor representations to which those linguistic elements refer).	• Teachers should encourage word learning and language comprehension through: (1) dialogic reading, in which the adult asks questions related to the text that are intended to prompt dialogue; (2) "acting out" vocabulary or sentences through play with a physical representation of content depicted in the text; and (3) performing iconic actions to illustrate word meaning through gesture or pantomime. • Teachers can use these simple bodily movements to help learners understand more advanced concepts (e.g., opposing forces as argument opposition) as they develop.
• People normally accompany their speech with representational gestures (e.g., that depict action, motion, trajectory, shape, or location); when added to collective dialogue, gestures and full-body movements contribute significantly to effectively communicating spatial information and foster more positive attitudes toward science.	• Students should illustrate thoughts (including making mental models) on paper or whiteboards, especially in small groups, before sharing information to the rest of the class. *Rehearsing* the information in both words and gestures helps to make the learning "manifest" (understandable to others). • Students should work collaboratively to collectively make sense of information. • Teachers should assess students' developing understanding by attending to both their gestures and their body language. • Teachers should make instructional decisions on the basis of what they can *see* that was not understood.
• Gestures are spontaneous or purposeful movements of the body that often accompany speech and serve as a way to convey ideas or add emphasis to language as well as to mathematics. Gesture production unfolds over time and can predict the quality of one's argument. Students learn better from teachers who use gestures to provide scaffolding, and teachers' attitudes toward gesture correlate with their success.	• Teachers and students should engage in more collaborative gestures. • Teachers should consider how gestures support understanding and reveal learners' struggles and understandings. • Teachers should engage in positive attitudes about the efficacy of gestures. • Teachers should continuously attend to not only what learners say but also learner's movements and idiosyncratic forms of perception, and how learners interpret their embodied experiences (called *intercorporeal attunement*). Paying attention to these things can help teachers enforce perceptuo-motor activity at consequential moments. • Teachers need to be attentive to students' whole-body learning experiences and intentionally incorporate movement into learning activities, which can increase the connection between the physical environment and academic goals through situated learning.

Table 19.1
(continued)

Key findings	Actions/advice
• The extent to which people know their fingers predicts their achievement in mathematics. Evidence from both behavioral and neuroscience studies shows that when people receive training on ways to perceive and represent their own fingers, they develop better representations of their fingers, which leads to higher mathematics achievement. Even university students' finger perception predicts their scores on calculation tests.	• Teachers should provide multidimensional experiences in mathematics, with multiple opportunities to see and experience mathematics through touch, sight, drawing, and writing in words. • Teachers should encourage visual mathematics even into college, rather than memorizing or reliance on formulations.
• The collection of practices that educators use to attend to and engage with learners' ideas is known as *responsive teaching*. A fundamental aspect of responsive teaching involves making sense of learners' ideas and monitoring these ideas for the seeds of productive disciplinary understandings that can be used to bridge learners' intuitions with more formal concepts and practices.	• Responsive teaching involves (1) drawing out, attending to, and engaging with aspects of learners' ideas that have potential disciplinary value or substance and (2) engaging in ongoing *proximal formative assessment* (e.g., continuously monitoring students' ideas to adapt instructional support in the moment). • Teachers should try to reformulate learners' ideas in order to help them extend and connect these ideas with new STEM disciplinary understandings. One way to achieve this is through the practice of *revoicing* or *recasting* learners' contributions (i.e., reporting or restating verbatim), reformulating (modifying the content of), and/or elaborating (adding new content to) the ideas learners have shared. • Teachers should directly interact with learners' gestures when describing their embodied experiences with embodied learning technologies by (1) pointing out/highlighting aspects of the gesture and/or (2) contributing new dynamic gestural imagery to the gesture.
• All technologies have their own material affordances and sensorimotor contingencies, which frame and constrain a person's interaction with a device. Manipulatives activate real-world knowledge, leading to more accurate performance. A growing body of work focuses on computer-based and virtual manipulatives (augmented reality, AR).	• Teachers should encourage the use of concrete manipulatives (e.g., blocks, chips, Dienes blocks, Geotiles, balance scales, paper clips, popsicle sticks, and beanbags) and computerized or AR technologies created and vetted for learning. • Teachers should encourage solving mathematical problems with real-world objects when possible, rather than solving comparable symbolically presented problems.
• "Good" manipulatives are interactive and give good "affordances" and epistemic fidelity (i.e., real-life properties that can be manipulated and promote "deep" analogy).	• Teachers should consider the following when deciding whether and how to use a given manipulative: (1) identifying the target concept, considering how the object under consideration relates to the target concept; (2) considering what actions the object affords, and (3) considering how those actions relate to the target concept. • Teachers should root themselves in practices that exemplify interaction that supports conceptual modeling, including digital simulations as well as physical manipulatives, especially for physics and STEM fields.

(continued)

Table 19.1
(continued)

Key findings	Actions/advice
• Augmented reality (AR) technologies bring the added benefit of movement to learning and can improve both visuospatial capabilities and enhanced student-reported interest when compared with traditional instruction. New and affordable virtual reality (VR) systems allow educational designers to include more gesture and body movements into lessons for the classroom. While advanced (AR and VR) technologies can be initially confusing, after a period of accommodation, users find physical and logical boundaries in order to produce visualizations that make sense to them. Over time, users began to build a spatial awareness of the range of measurability and influence of the sensors, which allows them to begin to explore fields of their own creation. Students often need support to develop visuospatial awareness for three-dimensional (3D) science concepts.	• Teachers should incorporate AR devices that display authentic data captured by the internal sensors. • Designers and scientists should consider such principles when incorporating mediated content, including considering the following key principles of evaluation: (1) the sensation of presence, which designers must learn to support, and (2) embodiment and agency associated with manipulating content in 3D to give a learner more personal control (agency) over the learning environment.
• Learning happens through the body's sensorimotor engagement with the world, even if those are challenged or different in special populations. Learning materials are frequently purported to achieve accessibility when, in fact, they merely translate visual-based spatial reasoning instruction through other modalities, as a tactile version or description of a graph might do.	• Teachers and policy-makers must flexibly adapt to learners' sensorimotor diversities to embrace human variation, challenge notions of normalcy, and recognize the social nature of disability. • Researchers and designers can redesign preexisting successful embodied learning demonstrations for differently abled students to account for nonaffected sensory and motor domains.
• Knowledge is *fluid* and *dynamic* and depends on what we are doing at the moment, what we have done recently, and what our *long-term experiences with the world* are. Individuals with motor and sensory impairment will have different experiences over time that shape the way they come to understand the world. Individuals on the autism spectrum may have different perceptions of the motorically relevant features of objects and actions as well as with joint attention—the ability to share focus on an object or area with another person (Akhtar & Gernsbacher, 2007).	• Teachers working with individuals on the autism spectrum might benefit by breaking down instruction into actions and smaller steps and incorporating an explicit learning strategy, including relying more on visual cues rather than motor systems. • Teachers working with individuals on the autism spectrum should rely less on using joint attention, gaze and facial expressions of others to inform learning.
• Observational learning is important for acquiring and communicating knowledge. The mirror neuron system (MNS), in collaboration with other neural networks, may contribute to larger motor and social-emotional learning processes, including contagion, imitation, theory of mind, and empathy. The MNS responds	• Teachers should engage in demonstrating a skill, and students should engage in subsequent imitation or emulation to enhance observational learning. • Teachers should use goal-directed human movement to illustrate new concepts. • Students and teachers should both understand the goals of a lesson in order for the MNS to be engaged effectively. This requires teachers to

Table 19.1
(continued)

Key findings	Actions/advice
robustly to observation and imitation of face and hand actions. The MNS may also have strong connections with reward circuits, which may be activated by positive emotions.	communicate with students the goals and appropriate context for the information as well as their own intentions. Students should be encouraged to express pride, enjoyment, and hopes about their learning.
• Embodied approaches have been developed to treat adults with mental illness and improve emotional well-being. These approaches include body-based therapies and disambiguation of affective states through mindfulness and increased emotional granularity. Mindfulness-based programs involve observing and labeling one's internal experiences and improving granularity. Higher emotional granularity is also positively correlated with school success.	• Students are more likely to benefit from social-emotional learning interventions that are embedded in school culture across all staff and students, are consistently present in all environments, and have invited parental involvement. • Classrooms and school settings should capitalize on teaching emotion vocabulary and mindfulness to individuals to not only improve emotional interactions and regulation but also to improve attention, focus, and cognitive awareness, which all facilitate academic performance. • Teachers should consider adding in mindfulness practices into the classroom.
• Studies show the importance of emotion words (and emotion language) and the effect they have on embodied emotion. People who rank high on granularity are able to distinguish among similarly valenced emotions with ease. Individuals higher in granularity also report more flexible emotional regulation abilities, have a less reactive coping style, and are less biased by incidental emotions when making moral decisions.	• Labeling is often a part of cognitive behavioral therapy to treat emotional disorders. For example, early in development, teachers can pair basic emotion words with naturalistic pictures of people showing prototypic emotional "expressions" and label these emotional behaviors when they are seen in the classroom. Situational information can later be added to help understand such "expressions" in context, and the use of situational language can then be incorporated into the category knowledge.

Finally, to address step 4, we highlight the need to develop taxonomies to identify objectives and track outcomes to ensure that program objectives and competency requirements are being met. As a start, Johnson-Glenberg (chapter 15) provides an assessment tool protocol for evaluating embodied augmented reality applications.

Summary and Future Directions

In this volume, we present the latest research on embodied cognition as it applies to teaching and learning across the content areas. The authors' unique contributions to the literature include (a) highlighting the historical bases of cognitive science, (b) reviewing the philosophical and theoretical problems with the legacy of Cartesian dualism, (c) critiquing current disembodied approaches to teaching, (d) examining the phenomenological foundations of embodiment, (e) providing neuroscience and empirical validation for embodied cognition approaches by offering this new framework and its applications across educational disciplines, (f) utilizing a *Translational Learning Sciences Research* (Macrine & Fugate, 2021) approach to apply the latest clinical and empirical findings to learning, and (g) making suggestions for future research and theory development in the area of embodied cognition.

The collective chapters present a coherent interdisciplinary package of empirical findings translated into applications and principles to facilitate embodied learning across the curriculum. This evidence-based research is essential to building a baseline of embodied approaches that can be disseminated throughout the K-12+ curriculum and further field tested. This collection can also serve as a useful road map and valuable resource for future explorers of embodied cognition as they make their own connections for teaching and learning.

We believe this volume will help current and future educators and practitioners in grounding the seminal metaphor of mind as an embodied system, which will be essential in advancing integrated and interdisciplinary approaches for effective embodied teaching and learning pedagogy. Since this is an initial foray into a cross-discipline compilation of scientific evidence supporting embodied learning, we excitedly await further research and the development of additional pedagogical applications. We also anticipate embodied cognition's future for changing the way we teach and learn through its incorporation it in curriculum design, technology, teacher education programs, education psychology courses and textbooks, and special education. Embodied cognition's learning principles, described in this collection, are also relevant when we consider other interested groups, such as policy-makers, textbook publishers, and the general public whose learning is also required for educational practice to change. We invite researchers and stakeholders across the disciplines to engage in *Translational Learning Sciences Research* (Macrine & Fugate, 2021) to effectively and efficiently get research findings out to the educational community. Ultimately, the continued development of embodied cognition's pathways will contribute to the advancement of translating the research findings to embodied learning and into practice.

In sum, *Movement Matters* offers educational practitioners, scholars, and researchers a look at the untapped potential of embodied cognition applied to education, pedagogy, and teaching to help students reach their full potential. We encourage others to research, investigate, and explore approaches and applications of embodied learning—and the science behind it.

Notes

1. JSMF, Second Biennial Call for Pre-Proposals [2019]. https://www.jsmf.org/apply/teachers-as-learners/#studypanel
2. Steps adapted from the National Institutes of Health NCATS (2019) and Rubio et al. (2010).

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Resources

Abrahamson

Embodied Design Research Laboratory at UC Berkeley (https://edrl.berkeley.edu/). EDRL is a design-based research laboratory studying mathematical cognition and instruction by creating and evaluating theory-driven educational innovation using both traditional and cutting-edge media.

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Abrahamson, D. (2014). Rethinking probability education: Perceptual judgment as epistemic resource. In E. J. Chernoff & B. Sriraman (Eds.), *Probabilistic thinking: Presenting plural perspectives* (pp. 339–260). Springer.

Abrahamson, D. (2021). Grasp actually: An evolutionist argument for enactivist mathematics education. *Human Development, 65,* 77–93.

Boaler

Youcubed resources:

- Finger training activities: https://www.youcubed.org/wp-content/uploads/2017/03/Finger-Activities-vF.pdf
- Summer camps: https://www.youcubed.org/evidence/our-teaching-approach/
- Various mathematics resources: https://www.youcubed.org/tasks/ and https://www.youcubed.org/week-inspirational-math/
- Data science K-12 initiative: https://www.youcubed.org/resource/data-literacy/

Flood, Shvarts, and Abrahamson

- Mathematical Imagery Trainer: https://edrl.berkeley.edu/projects/gesture-enhancement-of-virtual-agent-mathematics-tutor
- Mathematical Imagery Trainer for Proportion (MIT-Proportion): Abrahamson, D., Lee, R. G., Negrete, A. G., & Gutiérrez, J. F. (2014). Coordinating visualizations of polysemous action: Values added for grounding proportion. *ZDM Mathematics Education, 46*(1), 79–93.
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in an embodied-interaction technological tutorial for mathematics. *Learning, Culture, and Social Interaction, 22,* Article 100316. https://doi.org/10.1016/j.lcsi.2019.05.003

- Embodied design implementations are available at https://embodieddesign.sites.uu.nl/activity/ (see Functions, Activity 1 for MIT-Proportion and Activity 2 for MIT-Parabola).

Gómez and Glenberg

Embodied reading resources:

- Video demonstration: Glenberg, A. M. (2021). Embodiment and learning of abstract concepts (such as algebraic topology and regression to the mean) [Manuscript submitted for publication]. *Psychological Research.*
- EMBRACE books: https://www.movedbyreading.com/embrace-books/
- Moved by Reading program (Glenberg, 2011; Glenberg, Goldberg, & Zhu, 2011). https://www.movedbyreading.com/
- Adams, A., Glenberg, A., & Restrepo, M. A. (2018). Moved by Reading in a Spanish-speaking, dual language learner population. *Language, Speech, and Hearing Services in Schools, 49*(3), 582–594. https://doi.org/10.1044/2018_LSHSS-16-0032. Evaluates the effectiveness of an English-only version and a Spanish-support version of an embodied reading comprehension intervention (Moved by Reading) consisting of three stages (physical manipulation, imagined manipulation, and transfer) for Spanish-English dual-language learners.

Hutto and Abrahamson

The Mathematics Imagery Trainer (MIT)is an interactive technological system designed to create opportunities for students to develop new sensorimotor schemes that emerge from mathematical concepts. In particular, MIT for Proportion is geared to support the construction of proportional equivalence. For more on the MIT and MIT for Proportion, visit https://edrl.berkeley.edu/design/mathematics-imagery-trainer. See the work of Anna Shvarts at https://embodieddesign.sites.uu.nl/activity and interact with several mathematics imagery trainers covering a variety of topics. See also the references to MIT and MIT-Proportion in Flood and Tancredi (chapter 12 in this volume).

James

The Cognition and Action Neuroimaging Laboratory at Indiana University-Bloomington, Karin James' Lab-Cognition and Action Neuroimaging Lab (CANLab) focuses on how actions affect cognition. Visit the laboratory online at https://canlab.sitehost.iu.edu/people.html.

Johnson-Glenberg

AR-VR-XR

- For more on SMALLab Learning, go to https://www.smallablearning.com/videos.
- *Catch a Mimic* and *Mimic Go*, the new WebXR version, can be found at www.embodied-games.com.
- For more on *Titans of Space-Mobil* version in the Go headset, v. 2.5.5, go to http://www.drashvr.com/titansofspace.html.
- For more on *Virtual Be Einstein* to improve self-esteem, see Banakou, D., Kishore, S., & Slater, M. (2018.). Virtually being Einstein results in an improvement in cognitive task performance and a decrease in age bias. *Frontiers in Psychology 9,* Article 917. https://doi.org/10.3389/fpsyg.2018.00917. The video for the report is at https://www.youtube.com/watch?v=TAEM5OlFbnw.

- Also see Lindgren, R., Tscholl, M., & Moshell, J. M. (2014). *MEteor: Developing Physics Concepts through Body-based Interaction with a Mixed Reality Simulation*. 217–220. Paper presented at 2013 Physics Education Research Conference. https://doi.org/10.1119/perc.2013.pr.042

Kaschak and McGraw

- Enacted Reading Comprehension (ERC): Kaschak, M. P., Connor, C. M., & Dombek, J. L. (2017). Enacted reading comprehension: Using bodily movement to aid the comprehension of abstract text content. *PLoS One, 12,* Article e0169711. https://doi.org/10.1371/journal.pone.0169711
- Language in Motion (LIM): Connor, C. M., Phillips, B. M., Kaschak, M., Apel, K., Kim, Y., Al Otaiba, S., Crowe, E. C., Thomas-Tate, S., Johnson, L. C., & Lonigan, C. J. (2014). Comprehension tools for teachers: Reading for understanding from kindergarten through fourth grade. *Educational Psychology Review, 26,* 379–401. https://dx.doi.org/10.1007/s10648-014-9267-1

Megowan-Romanowicz

For magnetic fields, see *Visualize the Invisible* is a tool for teaching and learning about magnetic fields with augmented reality:

- https://www.magna-ar.net/
- https://www.modelinginstruction.org/?s=embodied

*Free on Google Play

See also the American Modeling Teachers Association (AMTA), a professional organization of teachers, by teachers, for teachers, who use Modeling Instruction in their STEM teaching: https://www.modelinginstruction.org.

Schenck, Walkington, and Nathan

- uwmagiclab.org—website for the MAGIC Lab at University of Wisconsin–Madison
- Embodied Mathematical Imagination & Cognition: https://www.embodiedmathematics.com
- The Hidden Village: Mathematical Reasoning through Movement—The Hidden Village on Kinect: https://multiplex.videohall.com/presentations/1662

*And you can join in with Embodied Math on Twitter @embodiedmath.

Tancredi, Chen, Krause, and Siu

Special Education Embodied Design at the Embodied Design Research Laboratory: https://edrl.berkeley.edu/projects/special-education-embodied-design-speed/

- Balance Board Math (Tancredi): https://edrl.berkeley.edu/projects/balance-board-math/
- Magical Musical Mat (Chen): https://edrl.berkeley.edu/projects/magical-musical-mat/
- SignEd|Math (Krause): https://edrl.berkeley.edu/projects/signedmath/
- Tancredi, S., Chen, R. S. Y., Krause, C., Abrahamson, D., & Gomez Paloma, F. (2021). Getting up to SpEED: Special education embodied design for sensorially equitable inclusion. *Education Sciences & Society – Open Access*, *12*(1). https://doi.org/10.3280/ess1-2021oa11818

Vieyra and Vieyra

1. Vieyra Software: https://www.vieyrasoftware.net/

2. Magna-AR: https://www.vieyrasoftware.net/physics-toolbox-ar

3. Physics Toolbox: https://play.google.com/store/apps/details?id=com.chrystianvieyra.physicstoolboxsuite&hl=en_US

*Free on Google Play

**This work is funded by NSF Grant

4. Explorations of Static Magnetic Fields: https://www.magna-ar.net/lesson-ideas

More Embodied Design Apps

- 3D Multiplication Table: https://edrl.berkeley.edu/design/3d-multiplication-table/
  The 3D multiplication table is a three-dimensional embodiment of the 100 products in the familiar 10-by-10 multiplication chart. The result is an intriguing object-to-think-with that supports mathematical inquiry by making salient logical and quantitative properties that are embedded in the regular multiplication table yet are difficult to see therein.
- 4-Block Stalagmite: https://edrl.berkeley.edu/design/4-block-stalagmite/
  Sample Stalagmite is an interactive computer-based model. The model is a part of the ProLab curriculum designed by Dor Abrahamson initially at Uri Wilensky's Center for Connected Learning and Computer-Based Modeling (CCL) at Northwestern University and later at UC Berkeley.
- 4-Blocks NetLogo model: http://ccl.northwestern.edu/netlogo/docs/
  The 4-Blocks NetLogo model is an interactive computer-based embodiment of the 4-Block mathematical object, simulating an empirical probability experiment in which the randomness generator is a compound of four squares that each can independently be either green or blue. The model helps conceptualize relations among theoretical and empirical aspects of the binomial functions.
- Combinations Tower: https://edrl.berkeley.edu/design/combinations-tower/
  The 16 unique configurations of the 4-Block are arranged in the tower according to the number of white (green) cells in them, resulting in a 1-4-6-4-1 formation (the corresponding binomial coefficients). This is the anticipated shape of the outcome distribution from experiments with the marble box containing equal numbers of marbles of each color.
- Dice Stalagmite: https://ccl.northwestern.edu/netlogo/models/DiceStalagmite
  Dice Stalagmite is an interactive computer-based model. The model is part of the ProLab curriculum designed by Dor Abrahamson initially at Uri Wilensky's Center for Connected Learning and Computer-Based Modeling (CCL) at Northwestern University and later at UC Berkeley.
- The Eye Trick: https://edrl.berkeley.edu/design/the-eye-trick/
  The Eye Trick is an activity for grounding the concept of proportion in perceptual judgments of geometrical similitude. The "trick" is that students judge similarity by creating an optical illusion of identity. Later, they use a stretchy ruler to determine measures, and they tabulate these measures in what becomes a ratio table.
- Histo Blocks: https://ccl.northwestern.edu/netlogo/models/HistoBlocks
  Histo Blocks is an interactive computer-based model. The model is a part of the ProLab curriculum designed by Dor Abrahamson initially at Uri Wilensky's Center for Connected Learning and Computer-Based Modeling (CCL) at Northwestern University and later at UC Berkeley. The EDRL website features some of these latter models as relevant to our publications.
- Magical Musical Mat: https://edrl.berkeley.edu/projects/magical-musical-mat/
  A domain-general communicative platform that surfaces the embodied interactions of students in special education. Also see Chen, R.S.Y., Ninh, A., Yu, B., & Abrahamson, D. (2020, June 19-23). *Being in touch with the core of social interaction: Embodied design for the nonverbal* [Paper presentation]. In Proceedings of the International Conference of the Learning Sciences (pp. 1681–1684). International Society of the Learning Sciences, Nashville, TN, United States.

https://edrl.berkeley.edu/wp-content/uploads/2020/07/Chen.Ninh_.Yu_.Abrahamson.ICLS2020.MMM-1.pdf

- The Marbles Scooper: https://edrl.berkeley.edu/design/the-marbles-scooper/
  The Marbles Scooper is a random generator for probability experiments, a device for sampling a fixed number of marbles out of a vessel containing many marbles, such as a box with equal numbers of green and blue marbles. We have built scoopers that sample exact numbers of marbles—a 4-Block marble scooper and a 9-Block marble scooper. https://www.youtube.com/watch?v=SkUJxXd4qAA

- Mathematics Imagery Trainer: https://edrl.berkeley.edu/design/mathematics-imagery-trainer/
  The Mathematics Imagery Trainer (MIT) is an interactive technological system designed to create opportunities for students to develop new sensorimotor schemes from which emerge mathematical concepts. In particular, the MIT for Proportion (MIT-P) is geared to support the construction of proportional equivalence. We have done extensive research on this design and using variety of media.

Related Articles

Blaskeslee, S. (2012, April 2). Mind games: Sometimes a white coat isn't just a white coat. *New York Times.* https://www.nytimes.com/2012/04/03/science/clothes-and-self-perception.html. Article reports on an emerging field in psychology known as embodied cognition and describes a role-playing experiment on being a doctor—the effect of clothing on cognitive processes.

Boaler, J., & Chen, L. (2016, April 13). Why kids should use their fingers in math class. *The Atlantic.* https://www.theatlantic.com/education/archive/2016/04/why-kids-should-use-their-fingers-in-math-class/478053/. Evidence from brain science suggests that far from being "babyish," the technique is essential for mathematical achievement.

Cutraro, J., & Epstein Ojalvo, H. (2012, April 4). It's not all in your head: Designing embodied cognition experiments. *New York Times*. https://learning.blogs.nytimes.com/2012/04/04/its-not-all-in-your-head-designing-embodiedcognition-experiments/

McGinty, J. C., (2016, October 23). Turns out, counting on your fingers makes you smarter. *The Wall Street Journal.* https://www.wsj.com/articles/turns-out-counting-on-your-fingers-makes-you-smarter-1477065563. Research shows that children who have better perception of their hands tend to be more skilled at math.

McNerney, S. (2011, November 4). A brief guide to embodied cognition: Why you are not your brain. *Scientific American Guest Blog.* https://blogs.scientificamerican.com/guest-blog/a-brief-guide-to-embodied-cognition-why-you-are-not-your-brain/. "Cognitive science calls this entire [Western] philosophical worldview into serious question on empirical grounds . . . [the mind] arises from the nature of our brains, bodies, and bodily experiences."

Smith, C., & Walkington, C. (2019). Four Principles for designing embodied mathematics activities. *Australian Mathematics Education Journal, 1*(4), 16–20. Current research shows these types of activities have great potential to help students develop conceptual understanding. The authors present four principles for designing embodied mathematics activities and give examples of classroom activities illustrating each idea.

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Index

Abrahamson, D., xi, 19, 39–52, 179–199, 205, 207, 208, 211, 317–321
Abstract concept(s), 17, 18, 30–32, 49, 87–89, 94, 95, 128, 217, 219, 293, 318
Abstraction(s), 19, 27, 95, 103, 107, 109, 121, 128, 163, 219
Accessibility, 197–201, 208, 211, 212, 312
Action-based, 19, 91, 134
Action-oriented, 41, 50, 92, 266
Action-related, 28, 31, 95
Action verb(s), 27, 28, 78, 280
Active learning, 25, 245, 252
Affordance(s), 16, 18, 104, 107, 110, 114, 133, 148, 150–152, 157–159, 173, 209, 217, 220, 230, 237, 238, 243, 244, 251, 254, 279, 292, 307, 311
Alibali, M. W., 19, 44, 45, 55, 97, 121, 131, 133, 134, 143, 147–162, 218
Arndt, P., 25–39
Artificial Intelligence (AI), 6, 14, 16
Auditory xviii, 17, 28, 29, 93, 197, 198, 200, 205, 207–211, 249, 253, 261, 266, 278, 286, 292
Augmented Reality (AR), 217, 218, 220, 223, 224, 228, 230–232, 238, 311–313, 318–320
Autism, 19, 201–204, 210, 213, 263, 265, 275, 278–287, 297, 312
Avatar(s), 239, 241–243, 248, 253, 254
Aziz–Zadeh, L., 2, 3, 19, 193, 261–274, 301

Barsalou, L., 2, 3, 17, 18, 26, 28, 29, 31, 88, 91, 131, 163, 217, 275, 292
Behaviorism, 14
Boaler, J., 121–130, 309, 317, 321
Butera, C., 3, 19, 193, 261–273

Cartesian, 14, 50, 131, 132, 181
Cartesian dualism/duality, 14–16, 114, 131, 307, 313
Categorization, 59–61, 72, 112, 241
Chen, R., 197–216, 301, 302, 319–321
Clark, A., xvii, 2, 16–18, 41, 48, 93, 97, 104
Cognition theory, 34, 197, 200, 212
Cognitive load, 45, 170, 223, 238, 266
Cognitive processing, xvi, xvii, 1, 17, 100, 262, 295
Cognitive psychology, 6, 16, 91, 308
Cognitive science, xiv–xvi, xv–xvii, 1, 3, 5, 6, 21, 23, 25, 26, 39–43, 49, 91, 100, 110, 197, 308, 313, 321
Collaborative gesture(s), 131, 133, 135–143, 310
Communication, 44, 105, 107, 124, 125, 164, 171, 173, 174, 202, 204, 205, 263, 267, 268, 278, 309
Computational, xiii—xvi, xix, 3, 6, 14, 15, 39, 40, 173
Conceptual knowledge, 16, 29, 231, 275–279, 282, 284, 286
Construction(ism)(ist), 6, 15, 46, 79, 91, 97, 133, 153, 159, 202, 210, 211, 292, 293, 318, 321
Cortex, xviii, 26, 27, 29, 31, 46, 65–69, 71, 78, 261, 262, 264, 278, 280, 300
Cortical, 29, 78, 95

Davis, C., 19, 275–290, 297
Descartes, R., 14
Design-based research, 197, 199, 200, 212, 317
Digital, 7, 19, 32, 33, 103–109, 111–114, 193, 218, 226
Disembodied, 2, 3, 15, 44, 107, 109, 131

Educational practice(s), xix, 4, 19, 20, 39, 43, 44, 49, 57, 99, 134, 193, 275, 308
Eigsti, I.–M., 275–290
Embodied cognition, xiv–xix, xi, 1–7, 13–20, 26, 27, 31, 34, 40, 43, 49, 77, 81, 87–89, 91, 93, 97, 99, 103, 104, 111, 121, 131, 164, 197–200, 212, 217, 219, 262, 267, 307–309, 313, 314, 321
Embodied knowledge, 35, 180, 285, 293

Embodied learning, xi, 3, 6, 8, 18–20, 25, 44, 173, 179, 180, 183–186, 188, 191–193, 230, 251, 269, 282, 285, 286, 307, 308, 310–312, 314
Embodiment, 1, 26–33, 39–46, 55, 65, 80, 87, 91, 92, 97–100, 103, 107, 109, 164, 197, 200, 218, 219, 231, 238–242, 251, 254, 275, 279–281, 295, 296, 310, 312, 314, 318, 320
Emission theory, 226, 227, 231
Emotion, 2, 7, 26, 31, 259, 266, 268, 286, 291–297, 299–301, 307, 313
Emotional, 81, 88, 243, 263–265, 268, 269, 286, 291–300
Emotional granularity, 19, 291, 296–300, 313
Emotion perception, 295, 297, 300
Emotion words, 293, 295–297, 299, 300, 313
Empathy, 243, 250, 253, 254, 263–266, 301, 312
Enactivism, 42, 198, 199, 208, 212
Encoding, xviii, 18, 217, 239, 250, 280, 282
Extended Reality (XR), 238, 239, 254, 318
Eye-tracking, 185, 277, 284, 317

Features, 147, 148, 150–152, 154, 155, 157–159, 165, 213, 225, 264, 275–281, 312, 320
Finger, 7, 30, 31, 83, 121–123, 139–141, 180, 192, 206, 239, 244, 263, 292, 309, 311, 317
Flood, V., 46, 47, 179–196, 208, 317, 318
Four E('s) (4E('s), 2, 18, 49, 103–105, 107–110, 112–114
Fugate, J. M. B., xi, xix, 1–24, 291–315, 323
Functional Magnetic Resonance Imaging (fMRI), 18, 28, 64, 78, 92, 103, 264, 276, 309

Gaze, 1, 6, 28, 107, 121, 166, 185, 285, 312
Geometry, 131–133, 136, 140
Gibson, J., xvi, xvii, xix, 2, 16, 42, 55, 104, 150, 279
Glasersfeld, E. von, 15
Glenberg, A., 47, 49, 77–94, 97, 98, 100, 105, 110, 131, 147, 156, 157, 159, 217, 301, 309, 318
Goldin-Meadow, S., xix, 44, 46, 131, 135, 164, 173, 186, 218, 238
Gómez, L., 77–91, 94, 97, 301, 309, 318, 319
Grounded cognition, 32, 131, 292
Grounding, 17, 18, 29, 32, 78, 79, 87, 88, 89, 94, 131, 193, 199, 309, 314, 317, 320
Guided action, 63, 66, 199, 201, 209

Handwriting, 7, 33, 34, 55–63, 65–69, 71, 72, 106, 107, 111, 309, 310
Hofmann, C., 25–38
Hutto, D., 2, 18, 28, 39–52, 199, 318

Imitation, 19, 263, 264, 266–269, 312, 313
Immersive, 217, 227, 231, 237, 239, 241–244, 252
Impairment(s), 276, 278, 279, 312
Instructional gestures, 133, 134, 137
Intervention(s), 4, 17, 19, 33, 57–59, 85, 93–100, 122, 134, 142, 143, 185, 204, 269, 286, 297–300, 308, 310, 311, 318

James, K., xi, 2, 33, 55–76, 309, 318
James, W., 2, 16, 291
Johnson-Glenberg, M., 19, 97, 164, 179, 180, 217–219, 231, 232, 237–257, 285, 313, 318

Kaschak, M., 77, 91–102, 110, 319
Kiefer, M., 18, 25–38, 105, 276
Kinesthetic, 44, 110, 111, 134, 186, 200, 207, 209, 217, 239
Krause, C., 197–216, 319

Lakoff, G., 2, 17, 18, 26, 49, 95, 131, 163, 267, 293
Language comprehension, 26, 40, 77–79, 91–94, 102, 110, 119, 310
Learning environment, 149, 164, 165, 170–173, 201, 238, 312
Learning outcome(s), 5, 65, 106, 147, 223, 237, 239, 243, 267
Learning sciences, 5, 6, 19, 49, 307, 320
Learning strategy(ies), 5, 269, 284, 285, 312
Learning theory, 5, 215, 308
Letter knowledge, 34, 55–57, 59, 60, 282, 310
Letter perception, 55, 62, 63, 65, 67, 69, 72
Linguistic(s), 20, 40, 83, 91, 93, 94, 97, 193, 206, 207, 210, 287, 293, 294, 310, 315
Literacy, 7, 55–58, 60, 65, 72, 77, 94, 103, 104, 129, 219, 309, 310

Macrine, S. L., 1–10, 13–24, 292, 307–315
Magnet, 18, 67, 71, 92, 103, 172, 202, 217, 221–231, 244, 264, 268, 276, 309, 319, 320
Mangen, A., 33, 103–118, 324
Manifest(ed), 1, 19, 163, 171, 173, 310
Manipulable, 248, 253, 275, 278, 281, 285
Manipulative(s), 7, 19, 80, 81, 97, 98, 128, 134, 147–159, 219, 307, 311
Mapping, 19, 155, 156, 158, 229, 232, 249
Marquardt-Donovan, A., 19, 45, 55, 97, 147–161
Mathematical, xix, 6, 31, 32, 44, 45–52, 55, 58, 80, 87, 121, 123–125, 127–129, 133–137, 140, 142, 143, 147, 151–153, 155–157, 170, 179, 181–186, 193, 200, 201, 203, 205–208, 211, 213, 311, 317–321

Mathematics, 4, 5, 7, 9, 46, 47, 49, 50, 105, 106, 121–129, 131–144, 147, 149, 151, 153, 155, 179–184, 193, 202, 205–207, 212, 219, 307, 309–311, 317–319, 321, 323
McGraw, A., 77, 91–102, 319
Megowan-Romanowicz, C., 44, 143, 163–175, 218, 219, 231, 232, 239, 244, 249, 285, 319
Memory, xiv, xv, 7, 25, 27–33, 65, 86, 91, 111, 124, 134, 147, 217, 218, 238, 268, 277, 308
Mental representation(s), 2, 13, 17, 18, 41, 48
Merleau Ponty, M., 1, 15, 16, 42
Metaphor xiv, 2, 3, 6, 13, 15, 18, 20, 44, 45, 49, 95, 108, 238, 243, 293, 307, 314
Mindfulness, 7, 19, 259, 291, 297–300
Mirror neuron(s), 3, 17, 19, 193, 261, 262, 266, 307, 312
Mixed reality (MR), 238, 244, 245, 249, 252, 254, 313, 319
Modality, 26–28, 49, 200–204, 209, 210, 249, 276
Montessori, M., 2, 6, 17, 91, 149
Motor areas, xviii, 27–29, 32, 69, 86, 121, 152, 264, 280
Motor representation(s), 19, 93, 261, 310
Motor system, 2, 3, 13, 20, 26, 30, 59, 62, 63, 65, 66, 72, 78, 87, 159, 277, 280–282, 285, 312
Multimodal/multi-modal, vii, 26–28, 179, 180, 183, 184, 186, 188, 189–193, 200, 202, 218, 239, 249, 286
Multisensory, vii, 20, 103, 109–111, 114, 239

Nathan, M., 19, 44, 55, 121, 131–146, 152, 159, 199, 319
National Center for Advancing Translational Sciences (NCATS), 4, 307–308, 315
National Institutes of Health (NIH), 24, 307, 315
Neural, xvii, 2, 3, 6, 41, 50, 63–66, 71, 72, 92, 122, 198, 261–266, 269, 278–281, 284, 312
Neuroimaging, 1, 28, 30, 32, 33, 64, 69, 72, 124, 264, 309, 318
Neuroscience, 1–3, 5, 6, 13, 18, 20, 40, 92, 95, 100, 121, 122, 129, 198, 208, 261, 262, 269, 308, 311, 314

Pedagogical, 15, 19, 104, 134, 135, 205, 211, 218, 221, 223, 309, 314
Pedagogy, 2, 3, 5, 6, 9, 106, 109, 112, 242, 243, 251, 252, 307, 308, 314
Perception–action, 62, 199, 200, 208, 279
Perceptual systems, 17, 20, 49, 63, 65, 78, 92, 275, 277
Perceptuomotor, 62, 66, 72, 111, 179, 180, 185, 186, 193, 279, 310
Phenomenological, 16, 42, 201, 314
Physics, 83, 86, 163–165, 171–174, 218–226, 228, 231–232, 285, 311, 319, 320
Piaget, J., 2, 6, 17, 25, 26, 32, 34, 55, 279
Pirhonen, A., 103–118
Policy, 4, 43, 48, 49, 103–108, 112, 308, 312, 314
Premotor cortex, 261, 262, 264, 278

Quality of Immersive VR in education Rubric (QUIVRR), 237, 242, 243, 251, 252

Reading comprehension, 92–94, 97, 98, 147, 156, 157, 310, 318, 319
Reading skills, xix, 56, 96
Reenactment(s), 19, 188, 284
Responsive teaching, 179, 182–184, 186, 188, 190–193, 311
Robotics, 16, 42, 130
Rogoff, B., 2, 6, 17, 163, 175
Rubrics, 237, 240–243, 247, 251, 252, 254

Schenck, K., 44, 45, 131–145, 319
Semantic, 3, 26–28, 32, 93, 262, 277, 281, 285, 295
Sensorimotor-based theories, 45, 275–277, 284
Sensorimotor experience(s), 7, 25–27, 33, 34, 89, 92, 200, 206, 209, 276–278, 285, 286, 292
Sensorimotor learning, 20, 263, 268
Sensorimotor pattern(s), 47, 199, 293
Sensorimotor process(es), 2, 26, 131
Sensorimotor representation(s), 33, 93–95, 262, 267, 310
Sensorimotor system(s), 13, 30, 32, 163, 200, 276
Sensory systems, xvi, 3, 17, 63, 133, 200, 202
Shapiro, L., xi, xiii–xx, 2, 6, 11, 17, 40, 41, 43, 46, 49, 198
Shvarts, A., 50, 179–1965, 317, 318
Simulation, 3, 17, 18, 78, 79, 91, 93, 168, 244, 245, 261, 263–266, 268, 269, 284, 309, 319
Situated, 2, 15, 17, 18, 26, 131, 163, 164, 190, 210, 211, 218, 230, 292, 294, 310
Siu, Y., 197–216, 319
Smartphone, 108, 217, 220, 223–232
Social cognition, 7, 133, 259, 263
Social context(s), 14, 83, 135, 163, 265
Social interaction, 183, 203, 204, 210, 264
Sociocultural, 49, 79, 109, 111, 183, 193, 213
Somatosensory, 17, 122, 264
Special education, 7, 49, 197, 198, 200, 201, 211, 212, 314, 319, 320
STEM (Science, Technology, Education, Mathematics), 5, 7, 119, 179, 180, 182, 183, 188, 193, 219, 237, 245, 254, 307, 311, 319

Tactile, xviii, 17, 186, 197, 200, 207, 209, 211, 242, 247, 312
Tactile, xviii, 17, 186, 197, 200, 207, 209, 211, 231, 242, 247, 248, 312, 325
Tancredi, S., 19, 46, 47, 143, 197–216, 318, 319
Technology, 3, 19, 20, 84, 85, 103–109, 111–114, 129, 148, 179, 183, 184, 186, 193, 217–219, 232, 237, 244, 245, 251, 252, 307, 308, 314
digital technology, 104, 106, 108, 114
Therapy, 201, 286, 299, 313
Translational learning science(s), 4–7, 33, 307–309, 314
Two–dimensional (2D), 217, 219, 222, 223, 228, 237

Universal Design for Learning (UDL), 197–199, 207–211

Vieyra, C., 217–236, 320
Vieyra, R., 217–236, 320
Virtual, xii, 33, 46, 47, 98, 107, 111, 148, 164, 171–173, 218, 239–242, 244, 245, 248, 254, 307, 311, 317, 318
Virtual reality (VR) 7, 18, 97, 218, 237–247, 249–252, 254, 312, 318
Visual cues, 57, 153, 224, 230, 285, 312
Visualization, 129, 220, 222–227, 229, 230, 232
Visual perception, xiv, 55, 57, 63, 66, 67
Visual processing, 65, 68, 124, 128
Visual system, 63, 78, 277, 278, 295
Visual world paradigm, 277, 281, 283
Visuomotor, 29, 46, 57, 59, 72, 261
Visuospatial, 30, 31, 33, 34, 171, 221, 223, 312
Vocabulary, 7, 28, 30, 77, 79–89, 96, 97, 189, 211, 239, 299, 300, 309, 310, 313

Walkington, C., xix, 45, 131–145, 319
Wilson-Mendenhall, C., 16, 18, 19, 32, 291–306
Writing, xi, xix, 32–34, 46, 56–59, 61, 62, 64, 66, 67, 70–72, 103–105, 107–112, 114, 121, 125, 143, 247, 307, 311

Yee, E., 275–290